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Preface

This volume includes the articles presented at the "Xth International Conference of Production Research-Americas" (ICPR-Americas 2020), held virtually from Bahía Blanca, Argentina from December 9 to 11, 2020. This conference was organized by the local organizing committee of the city of Bahía Blanca and was sponsored by the *International Foundation of Production Research* (IFPR). This conference aims at exchanging experiences and encouraging collaborative work among researchers and practitioners from the Americas and the Caribbean region.

The first ICPR Americas conference, took place in November 2002 in Saint Louis, Missouri, USA under the general theme of "Production Research and Computational Intelligence for Designing and Operating Complex Global Production Systems". This conference generated very positive responses from the attendees. From then on, the ICPR regional meeting was held at alternate years. The second version of the ICPR-Americas was held in August 2004 in Santiago, Chile with the conference theme "Information and Communication Technologies for Collaborative Operations Management". The third edition of the ICPR-Americas held in Curitiba, Brazil, had the general theme of "Rethinking Operation Systems: New Roles of Technology, Strategy and Organization in the America's Integration Era". This instance sought to promote a deep discussion about the role of Production Engineering in the America's integration process. In 2008, the venue of ICPR-Americas was Sao Paulo, Brazil at the Universidade de Sao Paulo Campus. The conference had the theme "The Role of Emerging Economies in the Future of Global Production: Creating New Multinationals". Bogota, Colombia hosted in 2010 the fifth conference with the subject "Technologies in Logistics and Manufacturing for Small and Medium Enterprises". The sixth edition (2012) was organized around the topic "Production Research in Americas Region: Agenda for the Next Decade" by the University of Santiago de Chile in Santiago. In Lima, Peru, the 2014 edition of ICPR-Americas addressed the general theme of "Towards Sustainable Eco-Industrialization through Applied Knowledge.". The eight edition was held at Valparaíso, Chile in 2016, and more recently, in 2018, the ninth conference was held at Bogotá, Colombia under the topic „Improving Supply Chain Management through Sustainability"

ICPR-Americas 2020 was the first edition carried out in virtual mode, due to the COVID-19 pandemic. Thanks to the participation and commitment of the attendees, the conference was carried out successfully, allowing many young researchers to participate in an international conference, in a year in which these opportunities were scarce. The ICPR-Americas meeting space gave them the opportunity to share their work, as well as exchange ideas and points of view, all in the cordial atmosphere that characterizes the ICPR-Americas conferences.

ICPR-Americas 2020 was organized by a local committee of the National University of the South, supported by the university and IFPR.

The conference received more than 280 papers, of which 245 were accepted and presented during the conference. The nationality of the authors was representative of the vast

majority of the countries of America, not only South America, but also Central and North America. Something that enriched the international experience that each of the participants took from the conference.

A couple of events associated with ICPR-Americas 2020 were also held: the “SIMPOSIO INDUSTRIAL” and the “SEMINARIO de ENSAYOS ESTUDIANTILES”. Both events allowed to broaden the scope and attendance of the conference. The accepted and presented works of both events are compiled within this volume.

Finally, it only remains for us to thank the National University of the South, especially the Departments of Engineering and Mathematics, as well as the General Secretariat of Science and Technology, for the support provided to carry out the event.

March 2021

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ICPR-Americas 2020

PLENARY SPEAKERS

Manufacturing Scheduling: Old solutions for new problems?

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Abstract. The talk addresses how the production research community can cope with the incoming changes in technology, customers, and environment that are taking place and that we expect that will shape the future manufacturing scenarios. More specifically, the focus is on the scheduling business function and on how it can be performed in these new manufacturing scenarios. Three cases will be used to illustrate these aspects.

Keywords: Manufacturing Scheduling, Industry 4.0.

1 Introduction

A number of technological changes and environmental drivers –some of them summarized in Fig. 1– are dramatically changing the manufacturing landscape, so it seems pertinent to ask how these changes can affect the scheduling function. The potential impact of these changes is exemplified using three cases.

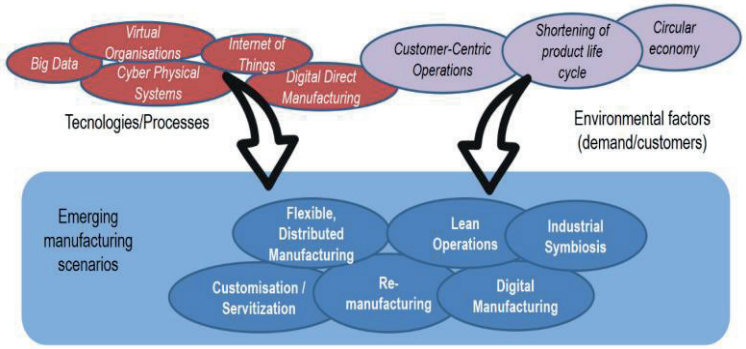

Fig. 1. New manufacturing scenarios

2 Some cases

The first case refers to scheduling Additive Manufacturing (AM) processes, which is an example of 'new' manufacturing scheduling problem that can be addressed using

the standard modelling methodology. So far, most of the research work has been done on the nesting problem (i.e. grouping the parts to be printed), with lesser work on scheduling, and even less in the combined nesting & scheduling problem. Furthermore, the preferred layout is the single/parallel machine, and the hybrid and assembly layouts (required in many cases to address the required polishing and finishing operations) have been insufficiently studied. This situation is rapidly changing, with a fast-increasing number of papers in this area (see e.g.[1] for a review).

The second case refers to the use of real-time information for rescheduling. The technological developments in Industry 4.0 envision a scenario where real-time data from different sources is potentially available. The big question is how this data can be used to improve scheduling performance, as it is clear that these real-time data could be used to reschedule the jobs in order to adapt to the shop floor status. The (limited) studies existing so far (e.g.[2,3]) seem to point out that these advantages should not be taken for granted, and are achieved only under a rather limited set of conditions, including performing complete rescheduling (as opposed to frozen sequences), or using efficient stochastic optimization methods and sophisticated rescheduling policies. This problem constitutes a rich vein of future research topics, ranging from computational complexity issues to reduce the computational effort of the stochastic optimization methods to devising intelligent triggers for rescheduling.

The third case refers to the potential of decentralized scheduling. Decentralized approaches for scheduling (such as the one presented in [4]) are known to be able to handle the extreme complexity of these manufacturing scenarios, however their performance is considered to be inferior to centralized (i.e. optimization) approaches. However, we show in an experiment that this performance gap quickly disappears with the uncertainty of the manufacturing scenario (in our experiment, this uncertainty is modelled using stochastic processing times). One key challenge is to combine both approaches so the advantages of both methodologies are obtained. To do so, new decision frameworks/architectures have to be developed.

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Perspectives and trends of Industry 4.0 in Latin America

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Abstract

In recent years, the advent of Industry 4.0 technologies has changed the world. Industry 4.0 is clearly not a buzzword or trend; Industry 4.0 and its successors (Industry 4.1? 5.0?, 4.01?) are here to stay. Despite its popularity, there is no agreement on what it exactly is and how it can be implemented; as of today, nobody can simply go shopping for Industry 4.0. Moreover, the adoption pace of such technologies has been dissimilar. Although no society in the world has disregarded the impact of this digital transformation, emerging economies sometimes struggle to "jump on the bandwagon". This comes at no surprise due to shortage of connectivity, infrastructure and… maturity. However, something needs to be done. This talk first introduces the current topics and technologies then addresses new trends and perspectives of Industry 4.0 in Latin America with special focus on production systems, urban transportation, and supply chain. The talk also examines potential areas of application and new research topics specific for the Americas region.

Digitalization of manual production and assembly processes for smart factories of the future

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Abstract.
Nowadays factories operating within the Industry 4.0 revolution require more and more reliable, fast and automatic tools for production analysis and improvement. Manufacturing companies, in which the human labor still has a crucial role, need digital tools and techniques able to manage complex production systems in terms of resource utilization, product mix, component allocation and material handling optimization.
Within this context, this plenary talk presents an original hardware/software architectures aimed at the human body digitalization and analysis during the execution of manufacturing/assembly tasks within common industrial workstations. The proposed solutions are based on the integration of the multiple sensors technologies with ad hoc software developed for productive and ergonomic analysis of the operator during his work. The suggested hardware integrates network of depth cameras, inertial sensors and other technologies, while original software infrastructure is conceived to automatically and quantitatively provide productive and ergonomic information. The former deals with human task analysis in terms of time execution and used space within the workplace, movements of hands and locations visited by the operator. The latter is focused on full body analysis implementing all the internationally adopted indexes as OWAS, REBA, NIOSH and EAWS. This double perspective makes the proposed digital solution for smart factories of the future a unique and valuable tool for industrial managers oriented to the workplace analysis and design in terms of productivity without neglecting the operator health. Real industrial applications of the proposed technology are presented and key results discussed analyzing multiple settings of production processes in which human operator plays a crucial role.

Keywords: Assembly system, Industry 4.0, Design and management, Internet of things, Smart manufacturing, Assembly line.

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Managing Macro Level Supply Chain Disruptions: Lessons from COVID-19

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Abstract

This talk discusses the current supply chain strategies that may have contributed to the disruptive impact of COVID-19. We suggest both short-term and long-term strategies that companies can utilize to minimize the impact of such a disruption in future. Specific emphasis is on flexibility and redundancy approaches, identifying vulnerabilities in networks, understanding topology of robust and resilient networks, and improving supply chain visibility

ICPR-Americas 2020

General Session

Advanced Energy Management: a review on Energy Management and I4.0

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Abstract. There are several reasons for an organization to begin managing its energy use more efficiently. Regulations, resource scarcity, environmental impacts, increased consumer pressure and increased competitiveness are all reasons that have highlighted energy management in recent years, both in the political and business landscape. In addition, associated with the expectation of increasing the efficiency of energy management systems, the application of technologies from Industry 4.0 is discussed. While promising, there are still few studies in the literature that address the relationship between these areas. Thus, through an integrative systematic literature review, this paper presents and discusses the concepts and characteristics of Advanced Energy Management Systems, which are based on the integration of Energy Management Systems and I4.0 technologies. The paper guides future works and companies that wish to apply Industry 4.0 technologies to their energy management systems by presenting potential benefits of this integration.

Keywords: Energy Management System, Industry 4.0, Energy Efficiency.

1 Introduction

Energy management (EM) has been widely discussed within organizations in recent years, given the scarcity of energy resources, intensification of legislation, greater awareness by clients, among other reasons. EM is understood as the activities and procedures that systemically seek to reduce both energy consumption and its related costs.

The use of renewable energy sources is an alternative for the long term, however a more efficient use of energy resources is characterized as an immediate countermeasure to the problems faced by organizations [1]. Then, in order to enhance energy management, authors such as [2] and [3] advocate the integration of energy management systems (EMS) with advanced information and communication technologies (AICT), characterized by the elements of Industry 4.0. Among the benefits pointed out in the literature, it can be highlighted the improvement of monitoring and measurement systems, the improvement of data collection and treatment, as well as contributing to and facilitating decision making.

Thus, based on the literature, the main objective of this article is to identify the elements and characteristics of this integration, in order to understand how EMS are correlated with information and communication technologies (ICT). In this paper, this new configuration is called Advanced Energy Management Systems (AEMS).

2 Research design

In order to identify the elements and characteristics of the integration between EM and AICT, the applied methodology was a systematic literature review (SLR).

After a preliminary search in the database, it was noticed that the number of studies that deal with the two themes together or relating them is still scarce. Therefore, as a research strategy, it was decided to carry out two SLR and correlate the themes. The first review deals with Energy Management and the second with Industry 4.0 (I4.0). This strategy was called Integrative Systematic Literature Review (see Figure 1).

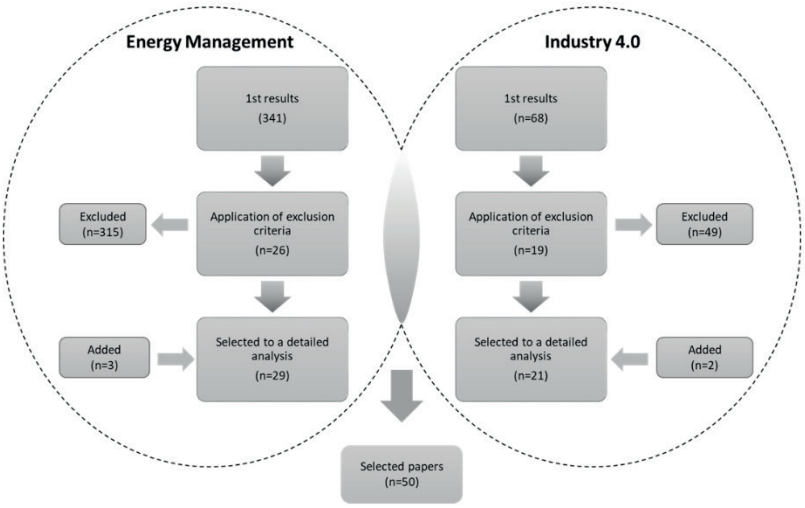

Fig. 1. Integrative Systematic Literature Review

Based on the procedure proposed by [4], the literature reviews assessed the papers registered in the Scopus database. After applying the keywords, a total of 409 papers were found. Following this first result, the papers were filtered through the application of exclusion criteria, leaving 45. After reading these papers, it was found 5 other relevant works (cited by previous authors), which were added at the end. Thus, the final base has a total of 50 works.

The literature reviews were followed by a content analysis that allowed authors to identify concepts and practices of EM and I4.0. Then it was possible to present how these two areas are connected.

3 Advanced energy management systems

EM can be understood as the effective and reasonable use of energy resources, to maximize profits and guarantee competitive positions to the company, through organizational and energy efficiency measures [5]. Although it can be described in a simplified way, this management is composed of activities and systematic procedures that require both the involvement of the areas directly linked to the production processes as well as the support areas [6].

The objectives of EM are to reduce the energy demand for products and services and eliminate waste, maintaining productive capacity [7]. To that end, EMS are used. In the literature, we can find several models, such as those proposed by [8], [6], [9] and [10], which guide the structuring of EMS.

The availability of relevant information is an essential element of EMS, so that not only can the system be properly structured, but also so that projects, activities and decisions are appropriate to the organization's reality and needs. For [8], I4.0 technologies are key elements in this context, as they facilitate the visualization and interpretation of information. Thus, it can be said that they add value to the available data.

I4.0, based on the combination of CPS and IoT, uses the available information and the communication network to expand the exchange of information between business and production processes, in a way that feeds the systems and adds value [11, 12]. Therefore, according to [13], I4.0 makes systems structure more flexible, improves event traceability, improves adherence to individual needs and facilitates decisions, among other benefits.

Thus, given this new scenario, where there is availability and transparency of information, intensification of connectivity between processes and flexibility of systems, EM benefits in several ways. The most evident is the wide availability of data, which allows organizations to carry out control at three different levels, starting with measuring the performance of a production plant, where there is a high level of data aggregation. The intermediate level is aimed at specific production lines or areas, while the last level, in greater detail, is the machine level [8, 14].

Moreover, using this greater availability of data and intelligent numerical controllers, equipment and systems can self-manage, so they have autonomy to adjust their settings and reduce their energy consumption.

Another important contribution of I4.0 to EMS is the ability to connect with other systems, so that integrations of EMS with ERP-type systems or CAx tools are possible [15]. This integration not only makes corrective actions faster, but also allows energy consumption indicators to be related and treated together with traditional performance indicators.

4 Conclusion

By means of an integrative literature review, this paper introduced the concept of Advanced Energy Management Systems, which are based on the integration between Energy Management and I4.0. Among the improvements enabled by this combination, it

can be highlighted the enhancement of control functions, integration of machines and systems, self-control and greater understanding of potential energy savings.

Thus, the use of I4.0 technologies is changing the way energy consumption is managed, moving from diagnostic to prognostic systems, helping to reduce energy costs in manufacturing.

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A simulation-optimization approach for the household energy planning problem considering uncertainty in users preferences

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Abstract. Power supply is one of the basic needs in modern *smart homes*. Computer-aid tools help optimizing energy utilization, contributing to sustainable goals of modern societies. For this purpose, this article presents a mathematical formulation to the household energy planning problem and a specific resolution method to build schedules for using deferrable electric that can reduce the cost of the electricity bill while keeping user satisfaction at a satisfactory level. User satisfaction have a great variability, since it is based on human preferences, thus a stochastic simulation-optimization approach is applied for handling uncertainty in the optimization process. Results over instances based on real-world data show the competitiveness of the proposed approach, which is able to compute different compromise solution accounting for the trade-off between these two conflicting optimization criteria.

Keywords: smart cities; energy planning; mixed-integer programming; simulation; multiobjective optimization.

1 Introduction

The paradigm of smart cities aims at increasing resource efficiency in several daily activities that citizens perform in urban environments. In the case of energy management, this aim is not only related to the amount of energy consumed, but also to the infrastructure required to distribute the energy [3]. The capacity of this infrastructure is often conditioned by peak consumption, as it should be able to distribute the energy during the periods of high demand without producing power outages. However, if consumption of a certain area is remarkably

unbalanced (having important variations along the day), this would required a large investment in infrastructure that will be idle the most of the time [10].

The introduction of time-of-use pricing in electricity bills for households is a major contributor to the overall efficiency of the electrical system, since it incentives citizens to have a smoother consumption patron, displacing the usage of electric devices from expensive peak hours to relatively cheaper off-peak hours. This behavior reduces the maximal instant power consumption of an urban area and, therefore, cuts back the required infrastructure investment to handle the peak and the risk of power outages [10]. However, usually off-peak hours, in which electricity is cheaper, are not preferred by users for using their appliances. This effect, which is known as inconvenience due to timing [1], can affect the well-being of the users. Therefore, there is a trade-off between both criteria, i.e., electricity cost and users satisfaction. Intelligent computer-aid tools may help users in the decision-making process of scheduling their deferrable devices [19].

This article proposes a novel mixed integer programming model for scheduling the deferrable electric appliances usage in households, which simultaneously considers minimizing the electricity cost and maximizing the users satisfaction. Users satisfaction measures to what extend the starting time and duration for appliances usage scheduled by the model match the users preferences–which is estimated through the analysis of historical data [4, 5, 22]. However, since this parameter can show certain variability between different days, a simulation-optimization resolution approach that considers this stochastic behaviour is devised. Therefore, the main contributions of the research reported in this work include: i) a compact mathematical formulation for the energy household problem, ii) the application of a stochastic resolution approach to consider uncertain users preferences, and iii) experimental evaluation over instances based on real-world data and analysis of the results.

The article is structured as follows. Section 2 presents the analysis of the main related works. The proposed mathematical formulation is outlined in Section 3. Section 4 describes the proposed simulation-optimization resolution approach. Section 5 describes the computational experimentation conducted to evaluate its effectiveness, and reports the numerical results for realistic problem instances. Finally, Section 6 formulates the conclusions and describes the main lines of future research.

2 Related work

Household energy planning has been considered as a complex problem in the related literature. The deterministic version (scheduling non-interruptible electric appliances) is associated with bin packing [16], a well-known NP-hard problem. Moreover, including uncertainty increases the complexity of the problem [17]. Several articles have considered uncertainty in this kind of problem. For a recent review, we refer to Lu et al. [18] for a comprehensive analysis of the topic and Liang and Zhuang [17], who focused on stochastic applications.

Uncertainty in energy household planning problems has been considered in several aspects. Chen et al. [6] considered uncertainties in the power consumed by the appliances and the renewable solar energy gathered by a photovoltaic array. A three-stages resolution process was proposed. First, a deterministic linear programming optimization model considering mean values for the appliances consumption and maximum solar power generation was solved. A stochastic procedure based on Monte Carlo simulation was applied to the resulting solution. The simulation considers different energy consumption rates of appliances and selects the consumption rate that minimizes the probability of shortcuts, which occurs when the overall consumption of electricity surpass a certain threshold value. Finally, an online adjustment of the previous (offline) solution was applied, which monitors the instant solar power generation and the consumption of appliances in real-time, compensating the household electric balance of the offline solution with a larger power storage in the battery or purchase from the grid. Hemmati and Saboori [12] proposed a particle swarm optimization algorithm to deal with uncertainty of photovoltaic panels in a similar problem. Assuming that the energy generated in the panels has a Gaussian probabilistic distribution, a Monte Carlo simulation was used each time the stochastic the stochastic function has to be evaluated to obtain a sample of the generation values.

Other researchers have used robust optimization, which aims at minimizing the impact of the worst-case scenario, considering that aleatory parameters have a bounded probabilistic distribution [1]. Jacomino and Le [13] presented a robust optimization approach to simultaneously minimize energy cost and maximize the comfort of users. They considered uncertainty in two aspects: the outdoor temperature and the solar radiation (related to weather forecast), that affect the energy to be consumed to satisfy the required indoor temperature, and users decisions related to not programmable services, i.e., despite the scheduled starting time and duration of the appliances the user can modified these conditions when actually using them. For handling uncertainty on users behaviour, a decomposition approach based on estimating the probability of occurrence of each scenario was used. Wang et al. [28] proposed a robust optimization approach for dealing with photovoltaic energy generation in household planning by using a mixed integer quadratic programming model, and Wang et al. [29] for dealing with uncertainty in hot water utilization and outdoor temperature that influences the usage of heating and air conditioning systems.

Other authors, although they have not consider uncertainty in their models, they have explored the trade-off that usually exists between electricity cost and users satisfaction through linear mathematical programming approaches -as it is performed in this work-. Among them, Yahia et al. [30] modeled a bi-objective problem considering these two objectives, which were combined by means of a linear weighted sum to form a unique objective function. They solved two single-household instances, i.e., a real South African case study and an artificial large instance, using LINGO. Additionally, they performed an extensive analysis of the sensitivity of the results to the modifications of certain parameters. The same authors expanded their work in [31] by considering as a third ob-

jective the reduction of the peak load. Moreover, in this last work they solved an instance considering several households simultaneously. They applied and compared three different multiobjective approaches: lexicographic optimization, normalized weighted sum and compromise programming.

This work contributes to the literature in several aspects. Firstly, a novel linear mathematical formulation of the household planning energy problem that explicitly considers users satisfaction as an objective function is presented. Approaches as such are not common in the related work [30]. Moreover, this is an improved mathematical formulation compared to the one presented in our previous work [20] for a similar conceptual model, having a smaller number of variables and restrictions. Secondly, this work considers stochastic users preferences which differentiates it to other linear programming applications in the related work [30, 31]. This leads to the final aspect that differentiates this work that is the application of the simulation-optimization Sample Average Approximation method to handle the uncertainty which has not been applied to this specific problem before.

3 Mathematical formulation

The household energy planning problem addressed in this article aims at reducing expenses of electricity in households while enhancing users satisfaction. This last objective was estimated by considering in which part of the day users prefer to use the appliances (inferred from historical data). Then, the mathematical formulation considers the following elements:

Sets:

- a set of users $U = \left(u_1 \dots u_{|U|}\right)$, each user represents a household;
- a set of time slots $T = \left(t_1 \dots t_{|T|}\right)$ in the planning period;
- sets of domestic appliances $L^u = \left(l_1^u \dots l_{|L|}^u\right)$ for each user u;

Parameters:

- a penalty term ρ^u applied to those users that surpass the maximum electric power contracted;
- a parameter D_l^u that indicates the average time of utilization for user u of appliance $l \in L^u$;
- a parameter C_t that indicates the utilization cost (per kW) of the energy in time slot t;
- a parameter P_l^u that indicates the power (in kW) consumed by appliance l;
- a binary parameter UP_{lt}^u that is 1 if user u prefers to use the appliance $l \in L^u$ at time slot t, 0 in other case;
- a parameter E^u that indicates the maximum electric power contracted by user u;
- a parameter E^{joint} that indicates the maximum electric power that the (whole) set of users U are allowed to consume;

Variables:

- a binary variable x_{lt}^u that indicates if user u has appliance $l \in L^u$ turn on at time slot t;
- a binary variable δ_{lt}^u that indicates if the appliance $l \in L^u$ of user u is turn on from time slot t up to a period of time that its at least equal to D_l^u;
- a binary variable ψ_t^u that indicates if the user is using more power than the maximum power contracted E^u.
- a binary variable Ψ_t^u that indicates if the user is using more power than 130% of the maximum power contracted E^u .

The problem aims at finding a planning function $X = \{x_{lt}^u\}$ for the use of each household appliance that simultaneously maximizes the user satisfaction (given the users preference functions) and minimize the total cost of the energy consumed. The mathematical formulation is outlined in Eqs. (1)-(11).

$$\max F = \sum_{u \in U} \sum_{l \in L^u} \sum_{\substack{t_1 \in T \\ t \leq |T| - D_l^u}} \left(\delta_{lt_1}^u \left(\sum_{\substack{t_2 \in T \\ t_1 \leq t_2 < t_1 + D_l^u}} U P_{lt_2}^u \right) \right) \tag{1}$$

$$\min G = \sum_{t \in T} \sum_{u \in U} \left(\sum_{l \in L^u} x_{lt}^u P_l^u C_t + \rho^u \left(0.3 \psi_t^u + 0.7 \Psi_t^u\right) \right) \tag{2}$$

Subject to

$$\delta_{lt}^u \leq 1 - \frac{D_l^u - \left(\sum_{\substack{t_2 \in T \\ t \leq t_1 < t + D_l^u}} x_{lt_1}^u \right)}{D_l^u}, \ \forall \ u \in U, l \in L^u, t \in T \tag{3}$$

$$\sum_{t \in T} \delta_{lt}^u = n_l^u, \ \forall \ u \in U, l \in L^u \tag{4}$$

$$\psi_t^u \geq \frac{\sum_{l \in L^u} P_l^u x_{lt}^u - E^u}{\sum_{l \in L^u} P_l^u}, \ \forall \ t \in T \tag{5}$$

$$\Psi_t^u \geq \frac{\sum_{l \in L^u} P_l^u x_{lt}^u - 1.3 E^u}{\sum_{l \in L^u} P_l^u}, \ \forall \ t \in T \tag{6}$$

$$\sum_{\substack{u \in U \\ l \in L^u}} P_l^u x_{lt}^u \leq E_{joint}, \ \forall \ t \in T \tag{7}$$

$$\psi_t^u \in \{0,1\}, \ u \in U \forall \ t \in T \tag{8}$$

$$\Psi_t^u \in \{0,1\}, \ u \in U \forall \ t \in T \tag{9}$$

$$\delta_{lt}^u \in \{0,1\}, \ \forall \ u \in U, l \in L^u, t \in T \tag{10}$$

$$x_{lt}^u \in \{0,1\}, \ \forall \ u \in U, l \in L^u, t \in T \tag{11}$$

Eq. (1) aims at maximizing the users satisfaction according to their preferences. Eq. (2) aims at minimizing the energy expense budget, which include the

charge for energy consumption and the penalization for exceeding the maximum power contracted. Eq. (3) enforces δ_{lt}^i to be one when the length of time an appliance will be on is equal or larger than the required by the user. Eq. (5) enforces ψ_j^i to be one if the user exceeds the maximum power contracted. Eq. (6) enforces Ψ_j^i to be one if the user exceeds the maximum power contracted for more than 30%. Eq. (7) enforces that the joint electric consumption by the set of users do not surpass a certain threshold maximum power. This equation is included when users are part of the same housing unit, e.g., an apartment building. Eqs. (8)-(11) establishes the binary nature of the variables.

4 The proposed simulation-optimization resolution approach for the stochastic household energy planning

Real-world data shows that considering users preferences (UP) as a deterministic parameter does not adjust to reality [15]. Users satisfaction can be modelled more accurately if uncertainty is taken into account for preferences in the model. Therefore, this article develops a resolution approach that considers this stochastic behaviour.

4.1 Bi-objective optimization

In order to handle the biobjective nature of the optimization problem presented in Section 3, a weighted sum optimization approach is applied. The weighted sum is a traditional method in the multiobjective optimization literature which has extensively been used in many applications, including for the energy household related problems [1]. Applying this approach, Eqs. (1) and Eqs. (2) are jointly optimized with Eq. (12), where w_F and w_G are the relative weights given to each criteria by the decision-maker.

$$\max H = w_F \frac{F - F^{best}}{F^{best} - F^{worst}} - w_G \frac{G - G^{best}}{G^{worst} - G^{best}} \tag{12}$$

One of the main drawbacks of this method is to know the actual best and worst values of each objective within the set of non-dominated solutions which are used for normalization (i.e., F^{best} and G^{best}, F^{worst} and G^{worst} in Eq. (12), respectively). In this work, for addressing this issue, the procedure proposed in Rossit [24] and applied in Rossit et al. [25] is used. This is a two step procedure. In the first step, the best and worst values of each objective are approximated by solving the single objective problem of each of the criteria involved. These values, which are likely to be dominated [2], are improved in the second step of the procedure. In this second phase, these best and worst values are used in the weighted sum formula (Eq. (12)) along with a biased combination of weights. This is, two different problems are solved, one problem using $w_F >> w_G > 0$ and the other problem using $w_G >> w_F > 0$. Finally, from the solutions of these last two multiobjective problems, the new best and worst values are obtained.

4.2 Sample Average Approximation method for considering stochastic users preferences

Formally, in a stochastic optimization problem with a probabilistic objective function, the expected value of this function should be optimized. In the case of the formulation described in Section 3, if parameters UP are considered stochastic, Eq. (1) should be replaced by Eq. (13).

$$e = \mathbb{E}_{\mathbf{P}} \left[F \left(\mathbf{\Delta}, \mathbf{UP} \right) \right]. \tag{13}$$

In Eq. (13), **UP** is the random vector of the stochastic users preferences and $\mathbf{\Delta}$ is the vector of decisional variables δ described in Section 3. In order to optimize Eq. (13), all the possible realizations of vector **UP** with its corresponding probability should be considered. Taking into account that the model of Section 3 uses a finite set of time slots, the set of possible realizations of **UP** is also finite. Particularly, there are $|T|^{\sum_{u \in U} |L^u|}$ realizations of this vector, each one constituting a possible scenario for the stochastic problem. For example, consider an instance in which the day is split in intervals of 30 minutes, i.e., $|T| = 48$, there two users (households) and each user has only two appliances ($|L^{u_1}| = |L^{u_2}| = 2$). Then, the number of possible scenarios would be $48^4 = 5,308,416$.

For the cases in which the large number of scenarios of real-world instances makes impractical to compute the exact expected value of Eq. (13), the expected value can be approximated with an independently and identically distributed (i.i.d.) random sample. This technique is called the "sample-path optimization" [23] or "sample average approximation" [26]. Thus, Eq. (14) is an estimator of the expected value of Eq. (13).

$$\hat{e} = \frac{1}{N} \sum_{j=1}^{N} F \left(\mathbf{\Delta}, \mathbf{UP^j} \right) \tag{14}$$

As aforementioned, the set of values $UP^1, ..., UP^N$, is an i.i.d. random sample of N realizations of the stochastic vector parameter **UP**. The optimization problem obtained when Eq. (14) is used instead of Eq. (13), is the sample average approximation optimization problem (hereafter SAA) and can be solved deterministically with commercial solvers. Clearly, the solution of the SAA problem depends on the realizations **UP** that are included in the random sample. Moreover, the larger the size of the sample (N), the smaller is the difference between Eq. (13) and its estimator Eq. (14). Particularly when $N \to \infty$, $\hat{e} \to e$ [14].

Different samples of size N (i.e., different set of realizations of the stochastic vector parameter **UP**) will shape different forms of Eq. (14). Therefore, the algorithms based on sample average solve the SAA problem several times with different samples [14, 27] and then select the most promising solution according to some predefined criteria as the final solution.

In this article the procedure proposed in Norkin et al. [21] and implemented in Verweij et al. [27] is applied. This is described as follows. Let $\hat{e}_N^1, \hat{e}_N^2, ..., \hat{e}_N^M$ be the values of Eq. (14) when solving M SAA problems, each one with a different sample of size N. Moreover, considered that $\hat{s}_N^1, \hat{s}_N^2, ..., \hat{s}_N^M$ are the solution (values of decision values) obtained when each of the aforementioned M SAA problems. An intuitive criteria for selecting the best solution among the M possibilities, would be to pick the solution with the best $\hat{e}_N$ value. A more sophisticated idea is to build an independent sample of size N', with $N' >> N$, and evaluate the solutions using this sample. Then, select the solution with the best value as it is expressed in Eq. (15) for a maximization problem.

$$\hat{s}_N^* \in \arg\max\{\hat{e}_{N'}(\hat{s}_N) : \hat{s}_N \in \hat{s}_N^1, \hat{s}_N^2, ..., \hat{s}_N^M\} \tag{15}$$

This idea takes advantage from the fact that even though using the large sample size N' for the optimization phase can be very time consuming (specially in NP-hard problems as the one addressed in this paper), using it for just for evaluation of the objective function Eq. (14) can be achievable in reasonable computing time [14].

5 Computational Experiments

This section describes the instances and methodology used for the evaluation of the proposed approach, and reports quantitative and qualitative results.

5.1 Problem instances

The instances construction is based on information from the REDD dataset [15]. As performed in Colacurcio et al. [7], instances with different sizes were considered. One of the key parameters to estimate was the users preferences. For estimating this parameter, information about the power consumption of the selected appliances on each household was analyzed. This involved cleaning the data from comparatively very small power consumption which are related to stand-by consumption of each appliance, for example, small screen leds. After this, for each combination of user and appliance, a probability of usage for each time slot was estimated (p_{lt}^u). With this probability, M instances were constructed for each sample size N as is described in Section 5.2. Additionally, from REDD dataset the mean power consumption of each appliance in KW (P_l^u) and the duration of the average time of utilization of each appliance (D_l^u) were estimated. When performing this noticeable differences were identified during the weekend, a behaviour that is usual for household users [8]. Therefore the instances were classified in weekdays and weekends.

Parameters E^u (maximum electric power contracted for each household) and C_t were obtained from the website of the Electric Company of Montevideo, Uruguay (`https://portal.ute.com.uy/`). Two instances size were considering, each one with two variations: weekdays (wd) and weekend (we):

– small ($s.wd$ and $s.we$). It has one household with seven deferrable appliances.
– large ($l.wd$ and $l.we$). It has two households with six and seven deferrable appliances respectively.

In the instances that corresponds to the small size Eq. (7) is not used since there is only one household and, thus, Eqs. (5) and (6) are enough for limiting the maximum consumed energy.

5.2 Experiment design

After some preliminary experimentation, the following sample sizes were chosen N = 50,200,500, 1000, 2000, 3000 and 10000. Within each sample size, the number of independent samples (M) was set to 100. The evaluation sample size (N') was set to 100000. The estimation of the ideal and nadir value for the weighted sum function were estimated with the procedure introduced in Section 4.1. This is performed within each N value. Additionally, five different weights configurations are used for exploring different trade-off between energy cost and user satisfaction (w_f,w_g): (0.99,0.01), (0.25, 0.75), (0.5, 0.5), (0.75, 0.25) and (0.01, 0.99). The SAA problems were solved with Gurobi [9] through Pyomo as modelling language [11].

Algorithm 1 Schema of a the Simulation-optimization (SO) approach.

initialize $SO(p^u_{lt}, N, M, \alpha, \beta)$
initialize list S of size M
for $m \leftarrow 0, m++, m \leq M$ **do**
  for $n \leftarrow 0, n++, n \leq N$ **do**
    for all $u \in U$ **do**
      for all $l \in L^u$ **do**
        for all $t \in T$ **do**
          initialize $t \leftarrow random(0, 1)$
          if $t \leq p^u_{lt}$ **then** $UP^u_{lt} = 1$
          else $UP^u_{lt} = 0$
          end if
        end for
      end for
    end for
  end for
  $S[m] \leftarrow$ **Solve MDR**$(\alpha, \beta,$ **UP**$))$
end for
return S

5.3 Experimental results

The experimental results are reported in Tables 1-2, for the small and large instances considering weekday and weekend usage conditions, respectively. These Tables report for each instance, sample size (N) and weight vector values the following results: the mean and standard deviation of the runtime, the user

satisfaction function F evaluated over N', the mean and standard deviation of the cost function G evaluated over N' (for the M different runs), and the values of F and G of the best compromising solution, i.e., the solution that has the minimal value of function H (Eq. (12)). It should be highlighted that since the cost function G (Eq. (2)) is deterministic, it is not affected by the sample size after the optimization process. In other words, for evaluation purposes: $G^N = G^{N'}$.

All the solutions of the SAA problems were solved to optimality since Gurobi was able to find solutions with 0% MIPGap for the compact mathematical formulation presented in Section 3 in relatively short computing times. The different combinations of weights were able to effectively explore the trade-off of the problem. Something interesting is that schedules that are biased towards minimizing the cost objective (with higher values of β) are more difficult to solve for Gurobi (computing times are as much of three times higher).

As expected, in general the larger the sample size N the higher the average the user satisfaction function value, since the expected value is better approximated by Eq. (14). Additionally, another important feature is that increasing sample size N led to a remarkable reduction of the variability of the results (measured through the standard deviation). Fig. 1 exemplifies this behavior, reporting the average and standard deviation of function F for the M independent samples for the three combinations with larger α, i.e., in which F has preponderance over the cost, in the large instance for the weekday patron.

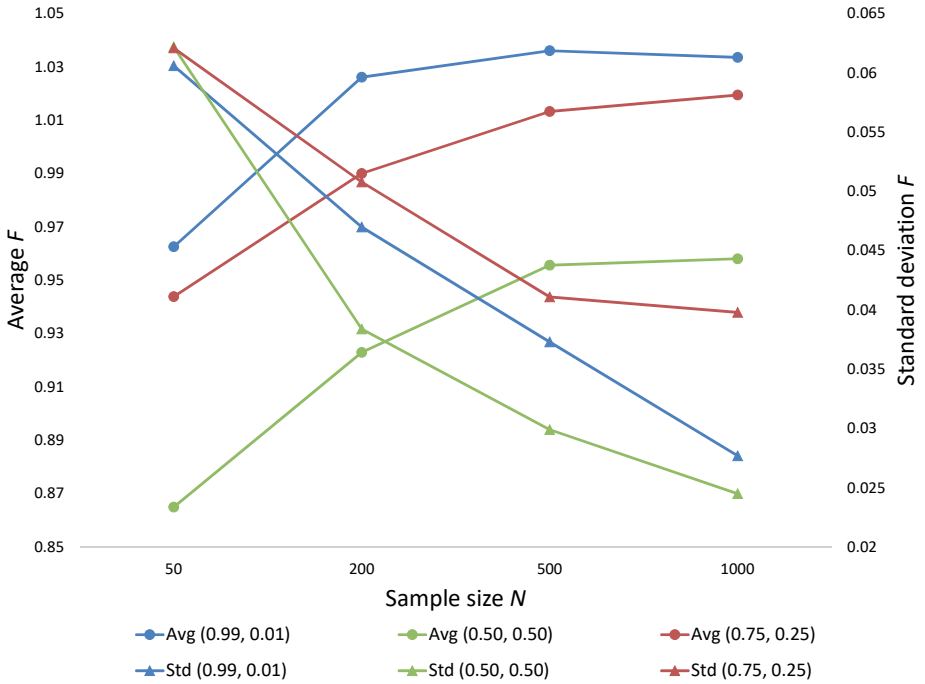

Fig. 1: Sensitivity analysis of average and standard deviation of F in l.wd instance.

Table 1: Results of small instance.

N	(α, β)	Time(sec)		$F^{N'}$		$G^{N'}$		$F(H^{N'}_{best})$	$G(H^{N'}_{best})$
		Avg	Std	Avg	Std	Avg	Std		
Small instance weekday (s.wd)									
50	(0.99,0.01)	0.04	0.07	0.5065	0.0405	115.91	8.65	0.5761	103.73
	(0.01,0.99)	0.13	0.09	0.2245	0.0192	89.39	0.00	0.2468	89.39
	(0.50,0.50)	0.08	0.08	0.4128	0.0464	96.84	2.36	0.4592	93.37
	(0.75,0.25)	0.05	0.07	0.4849	0.0476	103.63	4.40	0.5062	98.75
	(0.25,0.75)	0.11	0.08	0.3104	0.0478	90.99	0.95	0.2455	89.39
200	(0.99,0.01)	0.05	0.09	0.5445	0.0302	115.10	6.94	0.5877	104.83
	(0.01,0.99)	0.13	0.09	0.2342	0.0151	89.39	0.00	0.2462	89.39
	(0.50,0.50)	0.09	0.07	0.4270	0.0401	94.38	2.05	0.4608	93.37
	(0.75,0.25)	0.08	0.11	0.4835	0.0400	99.14	1.58	0.5170	98.20
	(0.25,0.75)	0.14	0.12	0.3036	0.0355	90.50	0.37	0.3048	89.74
500	(0.99,0.01)	0.06	0.11	0.5590	0.0251	113.08	2.86	0.5869	104.84
	(0.01,0.99)	0.14	0.10	0.2404	0.0088	89.39	0.00	0.2463	89.39
	(0.50,0.50)	0.11	0.11	0.4854	0.0266	98.07	0.72	0.4503	93.37
	(0.75,0.25)	0.10	0.13	0.5138	0.0432	100.75	2.82	0.5866	102.63
	(0.25,0.75)	0.14	0.13	0.3380	0.0301	90.86	0.44	0.3034	89.95
1000	(0.99,0.01)	0.02	0.01	0.5699	0.0229	112.93	1.11	0.5318	104.28
	(0.01,0.99)	0.10	0.01	0.2419	0.0073	89.39	0.00	0.2497	89.39
	(0.50,0.50)	0.07	0.01	0.5016	0.0235	98.15	0.50	0.4353	93.37
	(0.75,0.25)	0.05	0.07	0.5192	0.0324	99.54	2.00	0.5150	98.20
	(0.25,0.75)	0.09	0.01	0.3402	0.0236	90.80	0.12	0.3432	90.57
Small instance weekend (s.we)									
50	(0.99,0.01)	0.03	0.08	0.5271	0.0446	41.49	11.05	0.6095	29.66
	(0.01,0.99)	0.05	0.08	0.2725	0.0305	23.18	0.00	0.3160	23.18
	(0.50,0.50)	0.05	0.09	0.4864	0.0448	26.53	1.69	0.5298	25.41
	(0.75,0.25)	0.02	0.01	0.5348	0.0349	30.88	3.60	0.6003	28.81
	(0.25,0.75)	0.03	0.01	0.4163	0.0499	24.36	0.65	0.3334	22.05
200	(0.99,0.01)	0.03	0.08	0.5748	0.0358	38.37	9.51	0.5907	28.81
	(0.01,0.99)	0.05	0.09	0.2955	0.0152	23.18	0.00	0.3157	23.18
	(0.50,0.50)	0.08	0.12	0.4842	0.0280	25.08	0.48	0.5412	25.41
	(0.75,0.25)	0.04	0.08	0.5612	0.0242	28.95	0.88	0.5984	28.81
	(0.25,0.75)	0.08	0.11	0.3976	0.0346	23.67	0.28	0.3013	21.76
500	(0.99,0.01)	0.04	0.08	0.6048	0.0234	37.03	3.77	0.6005	28.81
	(0.01,0.99)	0.08	0.13	0.3011	0.0053	23.18	0.00	0.3157	23.18
	(0.50,0.50)	0.09	0.14	0.4783	0.0203	24.73	0.19	0.4809	23.33
	(0.75,0.25)	0.04	0.09	0.5611	0.0275	28.22	1.18	0.5316	25.41
	(0.25,0.75)	0.07	0.10	0.3174	0.0300	23.23	0.14	0.2948	22.76
1000	(0.99,0.01)	0.01	0.00	0.6176	0.0155	36.92	2.03	0.5901	28.82
	(0.01,0.99)	0.03	0.00	0.3027	0.0024	23.18	0.00	0.3054	23.18
	(0.50,0.50)	0.03	0.00	0.5467	0.0368	26.94	1.78	0.5321	25.41
	(0.75,0.25)	0.02	0.03	0.5845	0.0092	28.89	0.11	0.6084	28.81
	(0.25,0.75)	0.04	0.00	0.4665	0.0298	24.38	0.48	0.4355	23.76

Table 2: Results of large instance.

N	(α, β)	Time(sec)		$F^{N'}$		$G^{N'}$		$F(H^{N'}_{best})$	$G(H^{N'}_{best})$
		Avg	Std	Avg	Std	Avg	Std		
Large instance weekday (l.wd)									
50	(0.99,0.01)	0.07	0.07	0.9626	0.0606	200.60	15.23	1.0071	170.06
	(0.01,0.99)	0.40	0.15	0.3721	0.0350	131.41	0.00	0.4312	131.41
	(0.50,0.50)	0.21	0.10	0.8650	0.0622	144.47	2.86	0.7668	136.91
	(0.75,0.25)	0.19	0.15	0.9439	0.0621	160.94	9.52	1.0695	151.33
	(0.25,0.75)	0.24	0.08	0.7078	0.0886	135.99	1.62	0.6876	133.36
200	(0.99,0.01)	0.09	0.12	1.0262	0.0470	197.83	11.94	0.9115	165.68
	(0.01,0.99)	0.33	0.11	0.3890	0.0295	131.41	0.00	0.4322	131.41
	(0.50,0.50)	0.19	0.09	0.9230	0.0384	144.78	1.39	0.9230	140.15
	(0.75,0.25)	0.17	0.11	0.9901	0.0508	152.26	5.89	1.0213	145.69
	(0.25,0.75)	0.28	0.10	0.7248	0.0428	134.90	0.81	0.7450	134.03
500	(0.99,0.01)	0.08	0.12	1.0361	0.0373	195.71	8.13	1.0370	180.96
	(0.01,0.99)	0.31	0.09	0.3883	0.0277	131.41	0.00	0.4332	131.41
	(0.50,0.50)	0.22	0.14	0.9557	0.0299	145.26	0.33	1.0302	145.69
	(0.75,0.25)	0.16	0.11	1.0133	0.0411	151.98	5.51	1.0880	150.11
	(0.25,0.75)	0.29	0.12	0.7860	0.0441	136.49	1.26	0.7368	134.19
1000	(0.99,0.01)	0.08	0.07	1.0336	0.0277	195.49	8.24	1.0852	191.66
	(0.01,0.99)	0.32	0.08	0.3892	0.0263	131.41	0.00	0.4281	131.41
	(0.50,0.50)	0.19	0.08	0.9581	0.0245	145.21	0.22	0.9714	144.67
	(0.75,0.25)	0.13	0.05	1.0195	0.0398	151.37	5.50	1.0582	149.76
	(0.25,0.75)	0.27	0.09	0.7879	0.0364	136.46	0.96	0.7436	134.62
Large instance weekend (l.wd)									
50	(0.99,0.01)	0.10	0.13	1.0007	0.0620	287.69	13.86	1.1515	277.16
	(0.01,0.99)	0.33	0.12	0.4020	0.0190	197.55	0.16	0.3935	195.93
	(0.50,0.50)	0.17	0.12	0.8944	0.0620	209.69	2.72	0.9664	207.08
	(0.75,0.25)	0.15	0.11	0.9592	0.0693	222.08	9.62	1.0140	211.18
	(0.25,0.75)	0.22	0.12	0.7009	0.0834	201.07	1.49	0.6986	199.33
200	(0.99,0.01)	0.07	0.10	1.0614	0.0417	280.86	7.46	1.1160	271.33
	(0.01,0.99)	0.32	0.13	0.4091	0.0174	197.57	0.00	0.4347	197.57
	(0.50,0.50)	0.15	0.11	0.9796	0.0470	212.28	0.98	1.0626	211.73
	(0.75,0.25)	0.15	0.11	1.0018	0.0458	251.5656	13.567	1.1007	216.66
	(0.25,0.75)	0.22	0.13	0.8277	0.0563	204.74	1.33	0.7558	200.77
500	(0.99,0.01)	0.10	0.12	1.0944	0.0333	278.59	3.21	1.1403	268.53
	(0.01,0.99)	0.32	0.10	0.4139	0.0152	197.57	0.00	0.4345	197.57
	(0.50,0.50)	0.17	0.12	1.0065	0.0356	211.98	0.43	1.0541	211.73
	(0.75,0.25)	0.16	0.11	1.0171	0.0419	249.10	11.78	1.1226	216.16
	(0.25,0.75)	0.21	0.11	0.8301	0.0464	204.57	1.25	0.8179	202.28
1000	(0.99,0.01)	0.05	0.00	1.1060	0.0279	278.80	2.26	1.1365	271.58
	(0.01,0.99)	0.29	0.01	0.4129	0.0136	197.57	0.00	0.4319	197.57
	(0.50,0.50)	0.12	0.01	1.0155	0.0289	211.84	0.23	1.0491	211.73
	(0.75,0.25)	0.11	0.01	1.0347	0.0365	251.14	7.83	1.1169	216.16
	(0.25,0.75)	0.18	0.03	0.8362	0.0330	204.48	1.21	0.8124	202.19

6 Conclusions

This article studied the household energy planning problem, a relevant optimization problem that arises in the context of modern smart cities.

A novel bi-objective mathematical formulation of the problem was presented, accounting for uncertainty in the preferences of using each appliance. In this formulation, the aim is to schedule on a daily basis the usage of deferrable appliances while optimizing two conflicting objectives: the cost of the electricity–based on time-of-use tariff–and the users satisfaction. The users satisfaction is estimated through historical data of when (which part of the day) users prefer to use each appliance. However, since there is considerable variation of these preferences, a stochastic resolution approach was used to include the randomness of this parameter. The proposed problem was solved using the Sample Average Approximation method, which is a simulation-optimization approach that combines Monte Carlo simulation and deterministic mixed integer programming. Different real-world instances were considered and solved with different parametric combinations. The approach was able to propose different solutions that explore the trade-off between the two criteria in reasonable computing times. Particularly, for larger values of sample size the standard deviation of the results given by the method was significantly reduced.

Additionally, the initial tests performed in this work were execute in relatively small computing times even for the large instance. This shows the validity of the proposed integer mathematical formulation and the simulation-optimization approach as useful tools to perform practical load scheduling in smart homes. However, for enhancing performance of the model in a particular household, it is important to first gather specific data of that household to accurately estimate the key parameters of the model, such as the stochastic user preferences.

For future work, a crucial research line is to expand the computational experimentation. This should include using larger sample sizes and number of independent samples within each size (M) for exploring whether the accuracy of the solutions can be enhanced. Also, to study the competitiveness of the approach for larger instances in which buildings with more than two households are considered. Another way the instances can be enlarged is to include other kinds of appliances, such as non-deferrable loads, and renewable power generators within the household, e.g., solar or wind power generators.

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Seleção de um Sistema de Gerenciamento de Transportes numa Empresa do Setor Educacional

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Resumo. O uso da Tecnologia da Informação (TI) tem sido fator-chave para que empresas alcancem um nível de serviço adequado às expectativas de seus clientes, gerando um processo mais ágil e enxuto. Este artigo abordou as fragilidades nos processos de uma empresa do setor educacional cuja área de Logística ainda não emprega um sistema informatizado que auxilie no planejamento, na programação, no controle e na execução do transporte. Para tanto, analisou-se, com base em orientações técnico-teóricas relacionadas à TI e com suporte do método de tomada de decisão multicritério *Analytic Hierarchy Process* (AHP) acoplado ao modelo Benefícios, Oportunidades, Custos e Riscos (BOCR), a melhor alternativa para a seleção de um *software Transportation Management System* (TMS) considerando a realidade da empresa. A avaliação das alternativas s*oftware* próprio e *software* de mercado, foram efetuadas por uma equipe de especialistas. O resultado indicou *software* de mercado como a melhor alternativa, obteve a maior prioridade global, destacando-se como a melhor solução.

Palavras-chave: Sistema de Gerenciamento de Transportes, Fatores Críticos de Sucesso, Modelo AHP-BOCR, Empresa do Setor Educacional.

1 Introdução

O suporte de Tecnologia da Informação (TI) aplicado a diversos processos é o que tem garantido a organizações crescimento e visibilidade em um mercado cada vez mais competitivo. Assim, empresas que não lançam mão de tal suporte têm perdido oportunidades de negócio e de crescimento. De acordo com [1], as empresas devem investir em tecnologia e inovação para garantir a sua sobrevivência.

A melhoria da qualidade do serviço logístico – alcançada pela aplicação da TI – leva a maior satisfação do cliente e, desse modo, aumenta suas chances de fidelidade à empresa [2]. Considerando, portanto, que o resultado da aplicação das Tecnologias da Informação nos processos empresariais significa uma gestão mais eficaz e veloz na administração de recursos humanos e de equipamentos, é compreensível que as empresas busquem, constantemente, atualização tecnológica. Pois, como bem pontuam [3], o

crescimento das empresas, em um mundo globalizado que rompe, cada vez mais, as barreiras tempo-espaço, só se faz possível através de investimentos em tecnologia.

Assim, este estudo debruçou-se sobre uma empresa do setor educacional que não utiliza um *software* específico para o controle de informações em seu setor logístico, buscando identificar os problemas decorrentes da falta de uso de um sistema de gerenciamento de transporte (*Transporationt Management System* - TMS) e a alternativa mais adequada à organização: desenvolver um *software* próprio ou utilizar um *software* de mercado.

Por tratar-se de uma questão de integração de sistemas em uma complexa cadeia de suprimentos, compreende-se que o problema aqui levantado consiste em um problema multicritério e, portanto, deve ser abordado por meio da aplicação de um método de tomada de decisão multicritério (*Multiple Criteria Decision Making* - MCDM).

Há diversos métodos MCDM – *Analytic Hierarchy Process* (AHP), *Analytic Network Process* (ANP), *Measuring Attractiveness by a Categorical Based Evaluation Technique* (MACBETH), *Multi-Attribute Utility Theory* (MAUT), *Technique for Order Preference by Similarity to the Ideal Solution* (TOPSIS) – e cada um deles consiste em uma sistemática diferente para avaliar cada critério e como eles se correlacionam para uma avaliação geral [4]. De acordo com [4] e [5] dentre tais métodos, o mais utilizado e que permite uma análise holística das possíveis alternativas é o método AHP.

Por possuir características flexíveis e adaptáveis às necessidades do tomador de decisão e permitir um tratamento adequado, inclusive de aspectos subjetivos, esse estudo adotou o método AHP, que se baseia na definição de critérios – que neste estudo serão definidos de acordo com o modelo BOCR – e alternativas em uma estrutura hierárquica; no estabelecimento de valores a tais critérios e alternativas; na construção de uma matriz comparativa com estes valores; e, por fim, na conclusão e resolução do problema definido por meio da análise dessa matriz de comparação [6], [7], [8].

Neste contexto, o objetivo geral deste artigo foi analisar os impactos da ausência de um *software* TMS na empresa objeto de estudo e na aplicação do método AHP-BOCR para dar suporte e consistência à tomada de decisão, pela alta gestão, da melhor alternativa para a empresa na seleção desse *software*.

O artigo está organizado da seguinte forma: na Seção 2 apresenta-se a revisão da literatura, focada nos conceitos de sistema de gerenciamento de transportes, fatores críticos de sucesso para seleção e/ou implantação de sistema e método de priorização de alternativas. A Seção 3 faz referência à aplicação do AHP na seleção de sistema de gerenciamento de transportes. Finalmente, na Seção 4 estão as conclusões do trabalho, sendo seguidas pelas referências bibliográficas utilizadas neste texto.

2 Revisão da Literatura

2.1 Sistema Informatizado

Os sistemas de informação têm um papel cada vez mais importante na realização dos procedimentos logísticos nas empresas [9]. Isso porque, devido ao aumento do volume e da complexidade dos processos logísticos, os sistemas de informação são a única forma de gerenciar de maneira precisa o fluxo de produtos para os clientes.

Essa capacidade da TI em promover uma melhora significativa dos negócios empresariais também se encontra no trabalho de [2], cujas descobertas sugerem que a implementação da TI amplia diretamente a qualidade dos serviços relacionados à logística e, como consequência, auxilia na criação de competitividade entre empresas.

Uma outra função dos sistemas de TI é mediar a comunicação entre os diferentes departamentos da empresa, entre consumidores e contratados. Nesse sentido, vale a pena destacar a relação entre logística da informação e logística de transporte. A logística de transporte é frequentemente considerada um campo de pesquisa relativamente independente, que vê o transporte como a base do processo de operação logística e enfatiza o papel do transporte na conexão entre o fornecedor e o consumidor da cadeia de abastecimento [10]. Note-se também que um dos principais objetivos da logística é reduzir, constantemente, os custos dos processos logísticos, e esse objetivo aplica-se tanto ao processo de fornecimento quanto ao de distribuição – ambos relacionados à logística de transporte [11].

Portanto, a logística da informação é essencial para que tecnologias modernas sejam utilizadas de maneira eficiente na logística de transporte. Afinal, é a TI que permite que a ponte entre o fluxo de informações e a cadeia de fornecimento seja feita de maneira mais eficiente, pois é ela a responsável por integrar os dados do sistema ao transporte para o cliente com maior velocidade e exatidão, facilitando o processo, reduzindo custos e, por fim, aumentando a satisfação do consumidor.

Assim, se bem estruturado, meticulosamente planejado e equipado com a infraestrutura necessária, um sistema de TI deve ser capaz de entregar informações para todos os locais de trabalho, ao longo de todos os níveis da hierarquia organizacional da empresa, sem negligenciar nenhum dos objetivos logísticos em relação ao armazenamento de informação [12].

2.2 Sistema de Gerenciamento de Transportes

Como já exposto, as transformações tecnológicas têm exigido cada vez mais empenho das organizações no atendimento às demandas de seus clientes, que estão cada vez mais exigentes pelas possibilidades oferecidas ao dispor de um simples toque. Nesse cenário, uma empresa que necessita oferecer um produto ou um serviço, precisa fazê-lo da forma mais precisa e ágil, maximizando a qualidade e minimizando o custo.

No que tange à logística de transportes, por mais empenho que seres humanos possam oferecer nesse quadro, ele não pode ser comparado à eficiência e à agilidade de uma ferramenta tecnológica como o TMS, um dos sistemas mais utilizados em operações de logística e produção, juntamente com o *Enterprise Resource Planning* (ERP), o *Warehouse Management System* (WMS) e o *Intelligent Transportation System* (ITS) [13].

O TMS consiste em um sistema informatizado de transportes que, de acordo com [14], apresenta como principais funcionalidades o monitoramento e controle; o apoio a negociação e auditoria de frete; e o planejamento e execução. Deste modo, um TMS pode oferecer inúmeros benefícios à organização, como redução de custos, diminuição de erros e aumento na satisfação do cliente, uma vez que a ferramenta, além de conciliar diversos critérios para o cálculo das melhores alternativas, controla o fluxo de

informações através de todas as etapas de transporte, o que resulta em agilidade no atendimento das solicitações e em mais segurança, unidade e confiabilidade das informações. Esses benefícios convertem-se em vantagens competitivas, pois, como afirmam [15], a confiabilidade e a agilidade de resposta são peças centrais no dinamismo requerido pela atual conjuntura.

2.3 Fatores Críticos de Sucesso para Seleção e/ou Implantação de Sistema

Por definição, os Fatores Críticos de Sucesso - FCS [16], constituem as variáveis capazes de interferir diretamente no sucesso de projetos, ou nos objetivos, de determinada organização [17]. Os FCS devem guiar o início e o desenvolvimento do projeto em questão, sendo revisitados sempre que necessário, para que não se percam de vista os elementos que podem levar ao fracasso da empreitada [18]. Os FCS presentes na literatura [19], [20], [21], [22], [23], [24] e considerados rele-vantes à seleção e/ou implantação de um TMS no escopo do problema definido por este estudo estão relacionados na Fig. 1, com os respectivos artigos em que foram publicados.

Fatores Críticos de Sucesso	[19]	[20]	[21]	[22]	[23]	[24]
Avaliação de Desempenho (Monitoramento e Controle)	x	x	x	x		
Conversão e Acurácia da Análise de Dados		x	x		x	x
Complexidade do Projeto	x	x	x	x	x	
Composição da Equipe do Projeto	x	x	x	x	x	x
Comprometimento da Equipe do Projeto	x	x	x			x
Comunicação Interna do Projeto	x		x	x	x	x
Criticidade do Projeto	x		x		x	x
Customização Mínima (Alterações das Especificações)	x	x	x	x	x	x
Experiência do Cliente/Usuário	x				x	
Gerenciamento de Projeto		x	x		x	x
Habilidades de Gerenciamento de Mudanças	x	x	x	x	x	x
Líder do Projeto (Liderança)	x	x	x	x	x	
Metodologias de Desenvolvimento	x		x	x		x
Negócios Apropriados & Legados dos Sistemas de TI		x	x		x	x
Parceria com Fornecedor		x			x	
Planejamento Estratégico (Nível de Planej. do Projeto)	x	x	x			x
Reengenharia do Processo dos Negócios		x	x	x		
Suporte ao Usuário (Suporte do Fornecedor)	x	x	x	x		x
Suporte da Alta Gerência	x	x	x	x	x	x
Tecnologia	x					x
Tomada de Decisão Estratégica			x	x		
Treinamento e Educação do Cliente/Usuário	x	x	x	x	x	
Visão e Missão do Projeto	x	x	x		x	

Fig. 1. Compilação dos fatores críticos de sucesso.

2.4 Método de priorização de alternativas

O AHP foi criado por Thomas Saaty na década de 1970 e, hoje, é o método mais utilizado na resolução de problemas de análise multicritério por ter recebido especial atenção por parte de pesquisadores e por permitir que os tomadores de decisão em-preguem múltiplos critérios, inclusive os de natureza conflitante, de maneira quantitativa, para avaliar as opções disponíveis e, então, decidir pela melhor alternativa [25], [26]. O AHP consiste basicamente em três etapas [6]:

- Definição de uma hierarquia de decisão, a partir do estabelecimento de critérios e alternativas relacionados ao problema a ser resolvido.
- Atribuição de valores de importância para os critérios e valores de desempenho ou de preferência para as alternativas, com a construção de uma matriz.
- Revisão e síntese dos resultados.

Destaque-se que o método AHP possui dois meios para agregação das prioridades, sendo conhecidos como síntese normal e síntese ideal. Desse modo, pode-se empregar o uso da síntese normal para distribuição proporcional de recursos e/ou benefícios enquanto a síntese ideal pode ser aplicada para identificar a melhor alternativa dentro de um conjunto de alternativas distintas e sem dependência entre si [27].

O método AHP ainda permite que a sua mensuração seja realizada por meio da medição relativa ou absoluta. Na medição relativa as alternativas são comparadas aos pares e o resultado poderá sofrer alteração ou inversão dos dados finais enquanto na medição absoluta as alternativas são comparadas com um padrão de valores/desempenho pré-estabelecidos e, se combinado com a síntese ideal, garantirá a preservação do resultado [27].

A síntese ideal é indicada nas aplicações AHP se o objetivo principal é identificar a melhor alternativa. As combinações de medição absoluta com síntese ideal têm a vantagem de não permitir ordem inversa ou classificação de reversão. O método AHP exige uma seleção hierarquizada de critérios. Porém, quando a análise a ser feita é muito complexa, o mais adequado é que a estrutura adotada seja a de rede. Para tais casos, um dos critérios de decisão mais adotados é o modelo BOCR.

Com a aplicação do modelo BOCR, os critérios são organizados em pares opostos, em que B se opõe a C e O se opõe a R [7]. B e O são categorias valoradas como positivas, que remetem aos fatores que trazem consigo a certeza ou a possibilidade futura de receita/lucro, sendo que B representa os benefícios e O, as oportunidades; e C e R são categorias de importância negativa, relacionadas às possibilidades de impactos negativos, como perdas e prejuízos, sendo que C representa os custos e R, os riscos. Assim, a aplicação desse modelo permite uma análise mais complexa e proveitosa do que uma simples avaliação de custos *versus* benefícios, que não leva em consideração aspectos incertos, tantos positivos quanto negativos, da empreitada.

3 Procedimento do Método de Seleção Proposto

3.1 Objeto de Estudo

A organização objeto de estudo atua no mercado há 40 anos e suas principais atividades são: planejar, organizar, executar e supervisionar concursos, vestibulares e avaliações educacionais, a fim de selecionar pessoas por meio desses processos.

Muito embora a empresa possua um sistema de ERP (*Enterprise Resource Planning* – Sistema Integrado de Gestão Empresarial), MS Project (*Microsoft Project*) e outros sistemas que foram especificamente desenvolvidos para determinadas áreas, os processos estão apenas parcialmente imputados no sistema, não permitindo, assim, a plena utilização de toda a sua capacidade, que é a de promover a integração das atividades entre as áreas e, principalmente, fornecer a visão sistêmica de todos os processos interligados da organização.

Tendo em vista tal problemática, foram levantados, junto ao gerente e demais funcionários do setor, os impactos gerados pela falta de um sistema informatizado. Os pontos destacados estão elencados a seguir: (i) falhas de comunicação entre a área de Logística e os demais setores da empresa; (ii) desperdícios de mão de obra qualificada; (iii) sobrecarga de trabalho em determinados períodos e funcionários; (iv) desperdício de tempo com a realização de serviços manuais e de retrabalhos; (v) falta de sistema que controle o fluxo de saída e entrada de materiais; (vi) falta de sistema informatizado que seja capaz de subsidiar e dinamizar as informações necessárias; (vii) falta de sistema informatizado que seja capaz de informar: o peso e o volume do material a ser transportado por projeto, cidade e local de aplicação; modelos de roteirização, que adequariam o tipo de veículo à carga a ser transportada.

3.2 Definição de Especialistas e Aplicação do Modelo BOCR

Ao considerar as informações expostas nesta pesquisa, mostra-se relevante definir um grupo de especialistas composto por integrantes da organização, com a finalidade de se obter maior robustez na identificação, na análise e na validação dos dados levantados por este estudo. Deste modo, a composição da equipe que participou do processo de seleção foram 6 especialistas com formação nas áreas de logística empresarial (2), gestão de projetos, mestre em ciências, ciência da computação e ciências contábeis. Com 8 à 25 anos de experência na área, atuam no projeto de implantação do TMS nos cargos de gerente do projeto (1), responsáveis de TI (3), e usuários chave (2).

A seleção dos subcritérios foi baseada nos FCS (Seção 2.3) e a sua categorização foi realizada segundo o modelo BOCR. Aplicou-se essa definição para selecionar e associar adequadamente os subcritérios a cada categoria: Benefícios (B), Oportunidades (O), Custos (C) e Riscos (R). Assim, os especialistas concluíram que 12 subcritérios eram elegíveis para compor o referido estudo, os quais estão apresentados na Fig. 2.

Categorização BOCR	Código	Seleção de Subcritérios
Benefícios	B1	Avaliação de Desempenho (Monitoramento e Controle)
	B2	Reengenharia do Processo dos Negócios
	B3	Suporte da Alta Gerência
Oportunidades	O1	Composição da Equipe do Projeto
	O2	Gerenciamento de Projeto
	O3	Planejamento Estratégico (Nível de Planej. do Projeto)
Custos	C1	Negócios Apropriados & Legados dos Sistemas de TI
	C2	Suporte ao Usuário (Suporte do Fornecedor)
	C3	Treinamento e Educação do Cliente/Usuário
Riscos	R1	Customização Mínima (Alterações das Especificações)
	R2	Complexidade do Projeto
	R3	Experiência do Cliente/Usuário

Fig. 2. Seleção e categorização dos subcritérios.

4 Aplicação do Método AHP e Discussão dos Resultados

4.1 Aplicação do Método AHP

Depois de definidos critérios, subcritérios e alternativas, elaborou-se uma hierarquia para a aplicação do método AHP, apresentada e validada pela equipe de especialistas.

Por tratar-se da identificação da melhor alternativa, os especialistas estabeleceram o emprego da medição absoluta com a síntese ideal, uma vez que essa combinação não permite a ordem inversa ou classificação de reversão [28].

A Fig. 3 apresenta essa hierarquia correlacionada. No primeiro nível foram destacados os critérios: Benefícios (B), Oportunidades (O), Custos (C) e Riscos (R). No segundo nível foram elencados os subcritérios: B1; B2; B3; O1; O2; O3; C1; C2; C3; R1; R2 e R3. E, por fim, o terceiro nível compreendeu as alternativas: A1 e A2.

Após a conclusão dessa etapa, foram atribuídos valores de importância para os critérios e os subcritérios e valores de desempenho para as alternativas. Na sequência, utilizou-se o *software Excel* para a realização dos cálculos matemáticos e obtenção dos resultados de acordo com o método AHP.

Nesse estágio, iniciaram-se as comparações aos pares entre os subcritérios. Os valores de importância foram obtidos por meio de consenso dos seis especialistas participantes da pesquisa. As prioridades foram obtidas com a normalização do autovetor da matriz de comparações. As Tabelas 1, 2, 3 e 4 apresentam os resultados de prioridade para os subcritérios de cada critério Benefícios, Oportunidades, Custos e Riscos.

Observa-se na Tabela 1 que, para o critério Benefícios, o subcritério Reengenharia dos Processos de Negócios é o que possui maior índice de importância, seguidos pelos subcritérios Avaliação de Desempenho e Suporte da Alta Gerência. A razão de

consistência foi de 7% e ficou abaixo do limite tolerável de 10%. Portanto, essa matriz de julgamento pôde ser aceita.

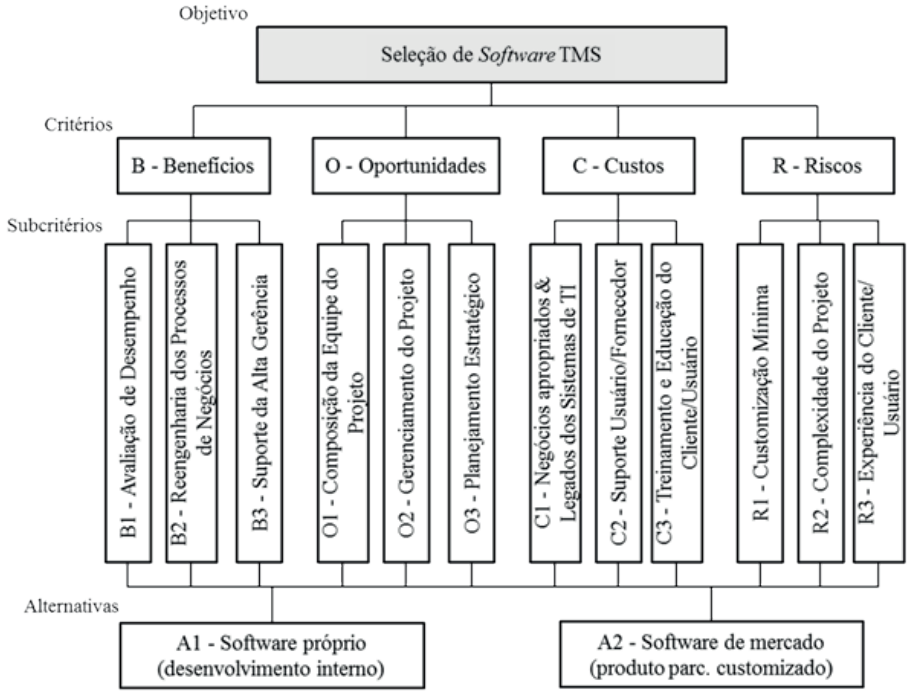

Fig. 3. Hierarquia para seleção e implantação de *software* TMS.

Tabela 1. Prioridade de subcritérios para benefícios.

	Avaliação de Desempenho	Reengenharia dos Proc. de Negócios	Suporte da Alta Gerência	Autovetor	Prioridade
Avaliação de Desempenho	**1**	1/7	3	0,8	14,9%
Reengenharia dos Proc. de Negócios	7	**1**	9	4,0	78,5%
Suporte da Alta Gerência	1/3	1/9	**1**	0,3	6,6%
Total (Soma)	**8,3**	**1,3**	**13,0**	**5,1**	**100%**

Observa-se na Tabela 2 que, para o critério Oportunidades, o subcritério Planejamento Estratégico é o que possui maior índice de importância, seguidos pelos subcritérios Composição da Equipe do Projeto e Planejamento Estratégico. A razão de

consistência foi de 7% e ficou abaixo do limite tolerável de 10%. Portanto, essa matriz de julgamento pôde ser aceita.

	Composição da Equipe do Projeto	Gerenciamento do Projeto	Planejamento Estratégico	Autovetor	Prioridade
Composição da Equipe do Projeto	**1**	3	1/7	0,8	14,9%
Gerenciamento do Projeto	1/3	**1**	1/9	0,3	6,6%
Planejamento Estratégico	7	9	**1**	4,0	78,5%
Total (Soma)	**8,3**	**13,0**	**1,3**	**5,1**	**100%**

Tabela 2. Prioridade de subcritérios para oportunidades.

Observa-se na Tabela 3 que, para o critério Custos, o subcritério Negócios Apropriados & Legados dos Sistemas de TI é o que possui maior índice de importância, seguidos pelos subcritérios Treinamento e Educação do Cliente/Usuário e Suporte ao Usuário/Fornecedor. A razão de consistência foi de 6% e ficou abaixo do limite tolerável de 10%. Portanto, essa matriz de julgamento pôde ser aceita.

Tabela 3. Prioridade de subcritérios para custos.

	Neg. Aprop. & Legados dos Sist. TI	Suporte ao Usuário/ Fornecedor	Trein. e Educação do Cliente/ Usuário	Autovetor	Prioridade
Neg. Aprop. & Legados dos Sist. TI	**1**	7	3	2,8	64,9%
Suporte ao Usuário/Fornecedor	1/7	**1**	1/5	0,3	7,2%
Trein. e Educação do Cliente/Usuário	1/3	5	**1**	1,2	27,9%
Total (Soma)	**1,5**	**13,0**	**4,2**	**4,3**	**100%**

Observa-se na Tabela 4 que, para o critério Riscos, o subcritério Complexidade do Projeto é o que possui maior índice de importância, seguidos pelos subcritérios Experiência do Cliente/Usuário e Customização Mínima. A razão de consistência foi de 6% e ficou abaixo do limite tolerável de 10%. Portanto, essa matriz de julgamento pôde ser aceita.

Tabela 4. Prioridade de subcritérios para riscos.

	Customização Mínima	Complexidade do Projeto	Experiência do Cliente/ Usuário	Autovetor	Prioridade
Customização Mínima	**1**	1/7	1/3	0,4	8,1%
Complexidade do Projeto	7	**1**	5	3,3	73,1%
Experiência do Cliente/ Usuário	3	1/5	**1**	0,8	18,8%
Total (Soma)	**11,0**	**1,3**	**6,3**	**4,5**	**100%**

Após a validação das matrizes de julgamentos, iniciou-se a análise para a definição de prioridade para cada critério BOCR. De comum acordo, os especialistas consideraram pertinente aplicar 25% de prioridade para cada critério: Benefícios, Oportunidades, Custos e Riscos. Assim, ao considerar que todos os critérios possuem a mesma prioridade de 25%, as prioridades globais foram calculadas pela multiplicação dos valores de prioridade de cada critério pelo peso dos subcritérios, por exemplo:

B1 = 0,25 . 0,149 = 3,72%, B2 = 0,25 . 0,785 = 19,63%, B3 = 0,25 . 0,066 = 1,64%

O mesmo cálculo foi aplicado aos demais subcritérios O1, O2, O3, C1, C2, C3, R1, R2 e R3. Os resultados estão dispostos na Tabela 5.

Tabela 5. Prioridade local e global.

Critérios e Subcritérios		Prioridade Local	Prioridade Global
Benefícios		**25,00%**	**25,00%**
	B1 - Avaliação de Desempenho	14,88%	3,72%
	B2 - Reengenharia dos Processos de Negócios	78,54%	19,63%
	B3 - Suporte da Alta Gerência	6,58%	1,64%
Oportunidades		**25,00%**	**25,00%**
	O1 - Composição da Equipe do Projeto	14,88%	3,72%
	O2 - Gerenciamento do Projeto	6,58%	1,64%
	O3 - Planejamento Estratégico	78,54%	19,63%
Custos		**25,00%**	**25,00%**
	C1 - Negócios Apropriados & Legados dos Sist. de TI	64,91%	16,23%
	C2 - Suporte ao Usuário/Fornecedor	7,19%	1,80%
	C3 - Treinamento e Educação do Cliente/Usuário	27,90%	6,97%
Riscos		**25,00%**	**25,00%**
	R1 - Customização Mínima	8,10%	2,02%
	R2 - Complexidade do Projeto	73,06%	18,27%
	R3 - Experiência do Cliente/Usuário	18,84%	4,71%

Ao analisar os resultados apresentados na Tabela 5, nota-se que as prioridades globais associadas a Benefícios e Oportunidades obtiveram o mesmo índice de importância (19,63%) para os subcritérios B2 e O3. Já para as prioridades globais associadas a Custos e Riscos, obtiveram um índice de importância próximo os subcritérios C1 (16,23%) e R2 (18,27%).

Em continuidade à aplicação do método AHP, a avaliação das alternativas foi realizada de modo qualitativo. Para tanto, utilizou-se a escala para medição absoluta, que contempla os níveis de qualidade e os valores de desempenho para cada um dos níveis. Assim, apresenta-se a escala para medição absoluta na Tabela 6.

Tabela 6. Escala para medição absoluta [29].

Nível	Prioridade
N1 - excelente	1,00
N2 - muito bom	0,83
N3 - entre bom e muito bom	0,67
N4 - bom	0,50
N5 - entre fraco e bom	0,25
N6 - fraco	0,00

A avaliação qualitativa das alternativas foi realizada para todos os subcritérios. Na Tabela 7, as prioridades da Tabela 6 substituem os julgamentos qualitativos.

Tabela 7. Avaliação quantitativa de *software* próprio e *software* de mercado.

Alternativas	Subcritérios											
	B1	B2	B3	O1	O2	O3	C1	C2	C3	R1	R2	R3
A1 - Software Próprio	0,83	0,83	0,50	0,50	0,67	0,67	0,67	0,67	0,83	1,00	0,50	0,83
A2 - Sotware de Mercado	0,67	0,67	0,50	0,83	0,83	1,00	0,83	0,50	0,83	0,50	1,00	0,83

As prioridades para as alternativas (Tabela 8) foram calculadas considerando o desempenho quantitativo e a prioridade global (Tabela 7), obtendo como resultado para a alternativa A1 (*Software* Próprio) 69%, exemplificado na sequência:

A1 = 0,83 × 3,72% (B1) + 0,83 × 19,63% (B2) + 0,50 × 1,64% (B3) + 0,50 × 3,72% (O1) + 0,67 × 1,64% (O2) + 0,67 × 19,63% (O3) + 0,67 × 16,23% (C1) + 0,67 × 1,80% (C2) + 0,83 × 6,97% (C3) + 1,00 × 2,02% (R1) + 0,50 × 18,27% (R2) + 0,83 × 4,71% (R3) = 0,69

O mesmo procedimento foi realizado para a obtenção do resultado da alternativa A2. Assim, a Tabela 8 expõe os resultados para as alternativas A1 – *Software* Próprio e A2 – *Software* de Mercado.

Tabela 8. Matriz de decisão - *software* próprio e *software* de mercado.

Alternativas	Subcritérios												Decisão
	B1	B2	B3	O1	O2	O3	C1	C2	C3	R1	R2	R3	
%	3,72	19,63	1,64	3,72	1,64	19,63	16,23	1,80	6,97	2,02	18,27	4,71	
A1 - Software Próprio	0,83	0,83	0,50	0,50	0,67	0,67	0,67	0,67	0,83	1,00	0,50	0,83	0,69
A2 - Sotware de Mercado	0,67	0,67	0,50	0,83	0,83	1,00	0,83	0,50	0,83	0,50	1,00	0,83	0,84

Observa-se na Tabela 8 que os subcritérios B3 (Suporte da Alta Gerência), C3 (Treinamento e Educação do Cliente/Usuário) e R3 (Experiência do Cliente/Usuário) receberam o mesmo peso de importância para ambas alternativas. Então, foi aplicado o valor de desempenho de 0,50 (N4 - bom) para o subcritério B3 e 0,83 (N2 - muito bom) para os subcritérios C3 e R3, pois os especialistas que, para essas comparações (alternativas *versus* subcritérios), deveria ser mantida uma avaliação igualitária. Assim, nota-se que a alternativa A2 (*Software* de Mercado) possui 84% de viabilidade enquanto a alternativa A1 (Software Próprio) possui 69%.

Como resultado final, a alternativa A2 destacou-se como a melhor solução e obteve, ainda, uma margem superior de 15% em relação a alternativa A1.

O resultado obtido por meio da aplicação do método AHP foi apresentado à equipe de especialistas, que pontuou a importância de se testar uma decisão com base na valoração de 50% para o critério Custos. Pois, para os especialistas, a partir do gerenciamento adequado dos Custos, pode-se obter uma avaliação mais crítica, que conduza à redução ou eliminação de desperdícios de recursos, que poderão ser convertidos em investimentos. Assim, esse critério apresenta-se mais sensível à decisão gerencial.

4.2 Discussão dos Resultados

Ao considerar o apontamento da equipe de especialistas e com o intuito de realizar o atendimento dessa nova proposta, aplicaram-se os mesmos cálculos e o resultado está apresentado, por meio de uma análise de sensibilidade, na Fig.4.

Na Fig. 4, observam-se duas linhas verticais. A linha vertical azul representa o peso inicial de 25% para o critério Custos enquanto a linha vertical verde representa a adequação proposta pelos especialistas, ou seja, a elevação do peso desse mesmo critério para 50%.

Por meio dessa representação gráfica, percebe-se que a alternativa A1 obteve elevação de 1% e que a alternativa A2 sofreu uma redução de 2%. Portanto, a alternativa A1 apresentou um resultado de 70% e a alternativa A2 de 82%. Ao analisar esse conjunto de dados e de informações, compreende-se que, independentemente das valorações para o BOCR, o resultado se manterá consistente e inalterado.

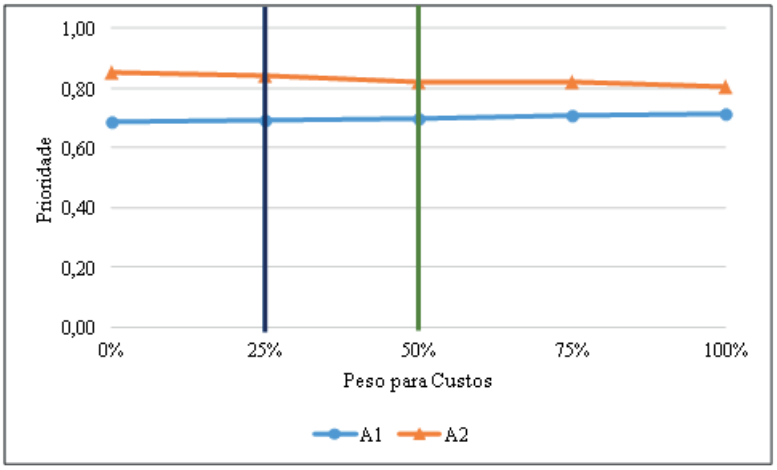

Fig. 4. Gráfico de análise de sensibilidade.

Os resultados supracitados foram apresentados, pela equipe de especialistas, ao corpo diretor da empresa, que, face à exposição, compreenderam a necessidade e os benefícios da implantação de um *software* TMS. Amparados pelos resultados consistentes apresentados pelo AHP, os diretores decidiram pela utilização do *software* de mercado, que permite a configuração de módulos e a customização de funções, de forma a atender às necessidades da empresa.

5 Conclusões

Ao considerar a complexidade da decisão e as particularidades da organização, propôs-se aplicar neste estudo o método AHP agregado ao modelo BOCR, que permitiu analisar as informações e os dados de maneira qualitativa e quantitativa, contribuindo para uma decisão imparcial e segura.

Após a apresentação dos resultados, a equipe considerou pertinente discuti-los amplamente, com o objetivo de ratificá-los. Os seguintes pontos foram suscitados: (i) a organização já possui licença e permissão para uso do módulo TMS de seu atual fornecedor de *software* ERP; (ii) a organização disporá de recursos financeiros para contratar os serviços de consultoria para a implantação do sistema e possíveis customizações de telas e relatórios; (iii) será alocado um especialista da TI para acompanhar todo o processo de implantação e parametrização do sistema, bem como para prover treinamentos; (iv) os analistas de desenvolvimento interno poderão, sempre que necessário, realizar customizações de telas e relatórios e, ainda, desenvolver melhorias no sistema após a sua implantação; (v) a organização dará continuidade ao investimento tecnológico para o desenvolvimento e suporte da área de Logística, avaliando a necessidade de agregar *softwares* complementares ao TMS, como: rastreadores e aplicativos *mobiles*.

Por fim, os especialistas destacaram a importância desse estudo para a empresa, uma vez que a solução para o problema em questão vinha sendo discutida há alguns anos e

diversas reuniões afins já haviam sido realizadas. A decisão, porém, sempre fora postergada pelos especialistas, considerando a dificuldade em se estabelecer critérios que: permitissem uma decisão unânime, possuíssem uma base criteriosa e não conduzissem a um resultado tendencioso. Assim, a equipe de especialistas demonstrou satisfação por colaborar, de modo ativo, na identificação da solução mais adequada para a organização, utilizando-se de uma ferramenta que conferiu, ao processo de decisão, a segurança e a confiabilidade que se fazem necessárias à resolução de problemas complexos.

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Desarrollo de un modelo matemático para el problema de enrutamiento e inventario con múltiples depósitos (MDIRP).

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Abstract.

The purpose of this paper was to develop a mathematical model to solve a multi-depot inventory routing problem (MDIRP). The objective of this optimization problem is to determine the optimal quantity of products to deliver to customers and to establish the route´s design to be followed by the vehicles in each of the depots. This was done to meet customer demand over a defined planning horizon.

In this case, the objective function was designed to minimize the costs associated with routing and, in turn, the costs of holding inventory at the customer and in the depots.

According to the literature review, the Genetic Algorithm (GA) metaheuristics was selected as a good technique to solve the problem. Several executions were started using different parameters to observe the behavior that this metaheuristic showed when the number of clients was modified.

The results of the experimentation were collected to observe for each instance, the routes that generated the best objective function. With this experimentation, the intention was to identify if the proposed algorithm could find reasonable solutions, within a reasonable computation time.

Keywords: Optimization problems, routing, planning periods, Multi-depot, Vehicle routing problem, genetic algorithm, inventory routing problems.

1 Introducción

En la actualidad, la logística es un proceso global que facilita un mejor desempeño de la actividad empresarial [1], dicho esto, tener un proceso logístico eficiente genera que una

empresa se pueda mantener posicionada en el mercado con el pasar de los días. Sin embargo, para lograr esto es necesario que se administren de manera eficiente los medios disponibles, además de tener algún tipo de planificación de lo que se debe producir para satisfacer a los clientes. Si no se hace todo esto, las empresas presentan problemas en la toma de decisiones y, por ende, se ve afectada no solo la corporación, sino los eslabones de la cadena de suministro [2]. Dicho esto, el desarrollo de soluciones al problema de planeación de rutas en el área de operaciones logísticas ha sido de gran ayuda a la hora de hacer planeaciones de pedidos, tiempo, distancias e inversión [3]. Uno de los modelos más conocidos es el problema IRP (Inventory Routing Problem), pues modela y optimiza algunas de las actividades más costosas de la cadena de suministro: el manejo de inventarios y la distribución física de productos [4]. Durante las últimas tres décadas, se introdujeron muchas variantes del modelo básico IRP. Las características que distinguen el modelo incluyen los tipos de demanda, si se trata como determinista o estocástica, además si el horizonte de planificación es el largo plazo o de corto plazo [5].

El modelo propuesto en esta investigación es una variación del modelo IRP el cual cosiste en un modelo de ruteo e inventario con múltiples depósitos (MDIRP), este modelo se acopla a las necesidades que presentan las empresas en la actualidad, ya que muchas de ellas al estar en ciudades de gran tamaño, recurren a tener varios depósitos para poder cumplir los pedidos solicitados por sus clientes.

Para este trabajo se desarrolló un modelo matemático que permite minimizar los costos de mantener inventario y los costos de transportar un producto, junto a la consideración de satisfacer la demanda de los clientes durante un periodo de tiempo determinado. Además, se selecciona la metaheurística Algoritmo genético (GA) como técnica para darle solución al modelo. Se usa el software Matlab para validar la eficiencia del modelo, todos los resultados e información que se recopilaron a lo largo de esta investigación se exponen en los resultados.

2 Formulación del modelo y método de solución

2.1 Descripción del problema

El problema abordado el problema MDIRP, que busca desde múltiples depósitos enviar las cantidades que satisfagan las demandas de los clientes en cada periodo de tiempo, considerando que así como los depósitos, los clientes tienen capacidad de almacenar inventario. La idea de problema es encontrar la solución óptima a las rutas de transporte, a las cantidades a enviar por periodo y a almacenar en cada uno, en el horizonte de la planificación, con el mínimo costo total. Para complementar la explicación del problema se realiza la siguiente descripción:

Se considera un grafo no dirigido G = (N, E), donde E hace referencia al conjunto de aristas $E\ \{(i,j)\colon i,j \in N, i \neq j\}$, N al conjunto de vértices. Se divide el conjunto N de tal manera que N= $(R \cup D)$, donde D = {1, 2, ..., d} es el conjunto de depósitos que entregan un producto al conjunto de minoristas R = {d + 1, d + 2, ..., d + i} mediante un conjunto de vehículos K={1, 2, ..k} en un horizonte de planeación T con una longitud t = {1, 2, ..., T} correspondiente a períodos de tiempo. Ahora bien, CTij representa el costo de ir desde un nodo i al nodo j, por medio de una matriz cuadrada. La capacidad de almacenamiento de todos los clientes CapC(i,t) está definida . Los vehículos también contienen una capacidad CapVk, es decir, la tasa de producción es limitada. Además, cada cliente i tiene una demanda Dit conocida en cada período t y puede ser atendida por vehículos del mismo depósito o desde diferentes (solo de ser estrictamente necesario). El nivel de inventario de cada cliente INV(i,t) no puede ser negativo.

2.2 Formulación matemática

Esta investigación aborda un modelo de programación lineal entera mixta. El objetivo del modelo es minimizar los costos generados por las actividades de transportar un producto, con la posibilidad de mantener inventario tanto en el depósito como en el cliente, satisfaciendo la demanda de cada cliente en cada período de tiempo. Dos características importantes de este problema son: (i) La demanda de un cliente en un periodo dado puede ser superior a la capacidad del vehículo, por lo tanto puede ser atendida por dos rutas diferentes en el mismo periodo. (ii) La demanda de un cliente en un periodo debe ser satisfecha, esto implica, que puede ser llevada en el mismo periodo o en los periodos previos.

2.2.1. Conjuntos

N Conjunto de todos los puntos $(R \cup D)$

R Conjunto de minoristas

D Conjunto de depósitos

T Conjunto de períodos de tiempo

K Conjunto de vehículos

2.2.2. Índices

i= {1, 2, 3…, R} Representa los clientes.

j= {1, 2, 3…, n} Representa los nodos.

d= {1, 2, …, D} Representa los Depósitos.

k= {1, 2, …, K} Representa los Vehículos.

t= {, 1, 2, …T,} Representa los Periodos.

2.2.3. Parámetros

$Dem_{i,t}$ Demanda del cliente i en el período t.

$CapC_i$ Capacidad de almacenamiento de cada cliente.

$CapV_k$ Capacidad de carga de los vehículos.

$CT_{i,j}$ Costo de transporte desde el nodo j al cliente i.

$CMI_{i,t}$ Costo de mantener inventario en el cliente i en el período t.

$CMD_{d,t}$ Costo de mantener inventario en el depósito d en el período t.

2.2.4. Variables

$Q_{i,d,k,t}$ Cantidad de producto enviado al cliente i usando el depósito d con el vehículo k en el periodo t.

$INV_{i,t}$ Inventario almacenado en el cliente i en el tiempo t

$Y_{i,j,d,k}$ Variable binaria igual a 1 si el vehículo k a partir del depósito d viaja directamente desde el vértice i al vértice j en el período t ((i, j) Ɛ N). 0 de lo contrario.

$Z_{i,d,k,t}$ Variable binaria igual a 1 si el vehículo k visita el vértice i del depósito d en el período t, 0 de lo contrario. (La variable no está definida cuando el vértice i es un depósito diferente de d, en este problema la posibilidad de visitar un depósito comenzando el recorrido desde otro uno no se considera.

F.O

$$Min\ z = \sum_{(i,j)\in N} CT_{i,j,d,k,t} * \left(\sum_{d}\sum_{k}\sum_{t} Y_{i,j,d,k,t}\right) + \sum_{i}\sum_{t} CMI_{i,t} * I_{i,t} + \sum_{t} CMI_{d,t}\left(\sum_{i}\sum_{d}\sum_{k} Q_{i,d,k,t}\right) \quad (1.1)$$

S.t:

$$\sum_{k}\sum_{d}\sum_{j\in R} Y_{i,j,d,k,t} \leq 1; \quad \forall \boldsymbol{i} \in R, \forall \boldsymbol{t} \in T \quad (1.2)$$

$$\sum_{k}\sum_{d}\sum_{i\in R} Y_{i,j,d,k,t} \leq 1; \quad \forall \boldsymbol{j} \in R, \forall \boldsymbol{t} \in T \quad (1.3)$$

$$\sum_{j\in N} Y_{i,j,d,k,t} + \sum_{j\in N} Y_{j,i,d,k,t} = 2Z_{i,d,k,t}\ ; \quad \forall \boldsymbol{i} \in R, \forall \boldsymbol{k} \in K, \forall \boldsymbol{d} \in D, \forall \boldsymbol{t} \in T \quad (1.4)$$

$$\sum_{i\in \mathrm{R}} Q_{i,d,k,t} \leq \mathrm{CapV}\, k; \quad \forall \boldsymbol{d} \in D, \forall \boldsymbol{k} \in K, \forall \boldsymbol{t} \in T \quad (1.5)$$

$$\sum_{k}\sum_{d} Q_{i,d,k,t} \leq \mathrm{CapC}\, i - I_{i,t}; \quad \forall \boldsymbol{i} \in R, \forall \boldsymbol{t} \in T \quad (1.6)$$

$$Q_{i,d,k,t} \leq \mathrm{CapC}_i * Z_{i\in \mathrm{R},d,k,t}; \quad \forall \boldsymbol{i} \in R, \forall \boldsymbol{k} \in K; \forall \boldsymbol{d} \in D, \forall \boldsymbol{t} \in T \quad (1.7)$$

$$\sum_{(i,j)\in E(S)} Y_{i,j,d,k,t} = \sum_{i\in S} Z_{i,d,k,t} - Z_{s,d,k,t}\ ; \quad \boldsymbol{s} \subseteq \boldsymbol{N}, \boldsymbol{s} \in \boldsymbol{S}, \boldsymbol{k} \in \boldsymbol{K}, \boldsymbol{t} \in \boldsymbol{T} \quad (1.8)$$

$$\sum_{k}\sum_{d} Q_{i,d,k,1} - DEM_{i,1} - INV_{i,1} = 0\ ; \quad \forall \boldsymbol{i} \in R \quad (1.9)$$

$$\sum_{k}\sum_{d} Q_{i,d,k,t} - INV_{i,t} + INV_{i,t-1} - DEM_{i,t} = 0\,;\ \ \forall \boldsymbol{i} \in R, \forall \boldsymbol{t} > 1 \in T \tag{1.10}$$

$$INV_{i,1} = 0 \quad Q_{i,d,k,t} \geq 0 \quad INV_{i,t} \geq 0 \tag{1.11}$$

$$Y_{i,j,d,k,t} \in \{0,1\}\ Z_{i,d,k,t} \in \{0,1\} \tag{1.12}$$

Las expresiones (1.2-1.3) garantiza que se cumplan las condiciones de ruteo, La expresión (1.4) indica que el vehículo que entre sea el que sale del nodo partiendo de su depósito usando el vértice (i, j). La expresión (1.5) no permite que la capacidad del vehículo sea excedida por la cantidad a entregar al cliente por cada periodo. La expresión (1.6) indica que la cantidad de unidades a ser enviadas desde los depósitos mediante sus vehículos no puede exceder la diferencia entre la capacidad y el inventario que tiene el cliente. La expresión (1.7) imita la producción disponible en cada depósito. La expresión (1.8) elimina los subtoures, las expresiones (1.9-1.10) establecen que la demanda del período debe ser satisfecha considerando su inventario actual e incluyendo la alternativa de dejar inventario para el siguiente período. La expresión (1.11) corresponde a las condiciones de no negatividad del modelo y por último la expresión (1.12) indica las condiciones de variables binarias del modelo.

3 Método de solución: Algoritmos genéticos

El problema MDIRP está definido como un problema NP-hard, la resolución de este tipo de problemas tiene numerosas aproximaciones, siendo las técnicas metaheurísticas las más utilizadas y, entre ellas, una de la más conocidas los Algoritmos Genéticos (AG) [6].

Para incluir las consideraciones del modelo MDIRP, inicialmente se definen sus principales componentes, para esto se toma como base el trabajo realizado por [7] donde el gen corresponde a cada uno de los arcos correspondientes del modelo y el cromosoma es conjunto de posibles rutas desde el punto inicial hasta el punto final del recorrido, cada cromosoma trae consigo una posible solución de la función objetivo que para este tipo de problemas es Minimizar el Costo. La figura 1, muestra cómo se va a presentar un vector solución para una instancia de 3 Depósitos, 2 vehículos por depósito, 1 período y 12 clientes, siendo depósitos= (0.1, 0.2…. ,d) y clientes depósitos= (1, 2, 3….. ,i).

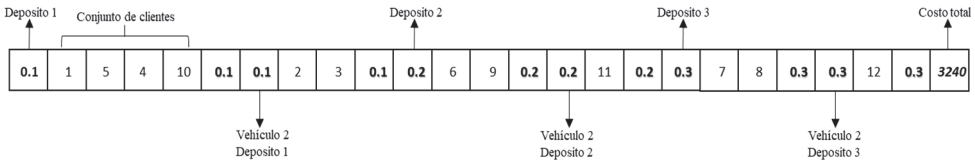

Fig. 1. Resultado Vector Solución.

A continuación, se expone como se realizan cada una de las fases del algoritmo genético para esta investigación.

3.1 Inicialización

La población inicial se genera de manera aleatoria, se origina un vector población inicial, el cual cambia para que durante la evaluación, los individuos muestren un fitness distinto. Este vector parte de la matriz de clientes, la cual a lo ancho presenta las características de estos clientes (demanda, capacidad, costos, entre otros) y a profundidad la cantidad de cromosomas que se generaron inicialmente. Cada vector población inicial corresponde a cada uno de los trozos del cubo los cuales solo contienen la lista desordenada de los clientes como se observa en la figura 2, además en este paso también se establece el vector depósitos el cual también es ordenado con base a los depósitos disponibles.

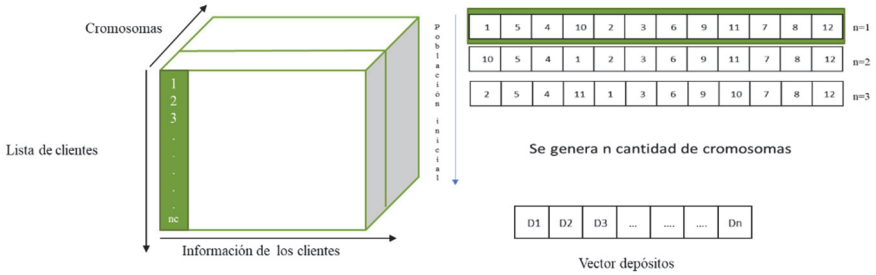

Fig. 2. Matriz de clientes y vector depósitos

3.2 Evaluación:

Se evalúa cada uno de los individuos de la población inicial asignándoles un valor según su calidad. Este valor numérico se llama fitness, y está asociado con los valores finales de costo (función objetivo).

En este punto, es necesario verificar si se cumple el criterio de parada. Si se incumple este criterio, se procede a aplicarsen los operadores genéticos, para este caso se usaron la selección y reproducción, cruce y mutación.

3.3 Selección y reproducción:

En este operador se verifican los individuos que contienen el mejor fitness, el método que se usa en este operador es la selección por torneo, la decisión radica en que este método de selección es uno de los más usados en relación con problemas de este tipo, se escogen individuos al azar de la población y entre ellos se compara el fitness reduciendo la población a la mitad, el que tenga mejor valor es el que pasa a la siguiente generación.
Una vez seleccionados los individuos mediante la selección por torneo, se procede a reproducir una cantidad de cromosomas que nunca deben superar el valor n de población inicial.

3.4 Cruce o crossover:

Cuando ya se tienen los mejores individuos (nuevos padres), se hace lo que se conoce como Crossover que consiste en mezclar el material genético. Una forma encontrada en la revisión de literatura y que se considera de las más sencillas, que se elige para este trabajo, es mediante un ‘‘One-point’’. Este consiste en elegir un punto de corte al azar para los dos individuos e intercambiar el material genético a partir de esta posición [8]. Lo anterior, se puede ver en la siguiente figura 3, la cual muestra el operador cruce con nuevos padres que contienen la mejor evaluación. Cabe indicar que se eliminan aquellos cromosomas cruzados que tienen repetido algún cliente.

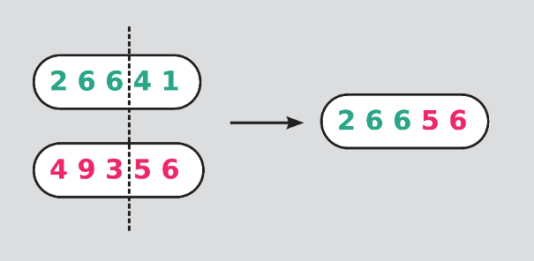

Fig. 3. Operador cruce.

3.5 Mutación:

Para realizar el último operador genético, se decide por la alternativa otorgada por [9], donde se recoge la tesis doctoral de Ruíz (2003), quien propone el uso de (SHIFT mutación), el cual demostra la superioridad y ventaja que tiene esta alternativa, sobre los otros tipos de operadores establecidos.
Inicialmente se genera un número aleatorio inicial que va de 1 hasta t, donde t representa el tamaño de la población. Este número permite identificar el individuo a mutar. Posteriormente, se tiene otro número aleatorio (0 o 1), este número hace referencia a la probabilidad de mutación, es decir, a la probabilidad de que el individuo seleccionado sea sometido a mutar. De esta manera, se comparan los 2 números aleatorios y si la probabilidad asociada al individuo es mayor o igual a la probabilidad de mutación establecida en el algoritmo, el individuo es mutado.
La estructura del operador SHIFT, es representada mediante dos fases. En la fase 1 se tiene los valores (R1, R2 y R3) siendo números aleatorios que están entre 0 y 1. R1 y R2 representan el inicio y fin del bloque del cromosoma a desplazar. R3, establece la posición del cromosoma donde se realiza el desplazamiento, esta posición no debe estar contenida dentro del bloque. Durante la fase 2, se desplaza el bloque hasta la posición R3, y se acomodan las demás posiciones del cromosoma. Ver figura 4.

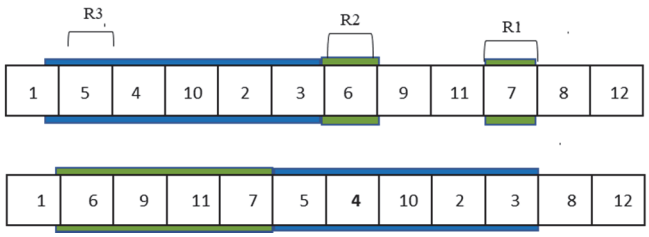

Fig. 4. Operador de mutación, nueva población.

Al tener el vector mutado nuevamente este pasa a evaluación donde se realiza la inclusión de los depósitos para la evaluación de su fitness, cada cromosoma era comparado con el anterior y así se obtiene la mejor solución de la corrida. Cabe recalcar que este proceso se realiza para un solo periodo, al ser este modelo multiperiodo el proceso del AG se realiza para cada uno de los periodos de planificación.

Una vez definido cada uno de los componentes del AG, se desarrolla este proceso en el software MATLAB. La forma gráfica que tendrá el vector solución de cada uno de los periodos de planificación de las instancias escogidas en esta investigación es la siguiente:

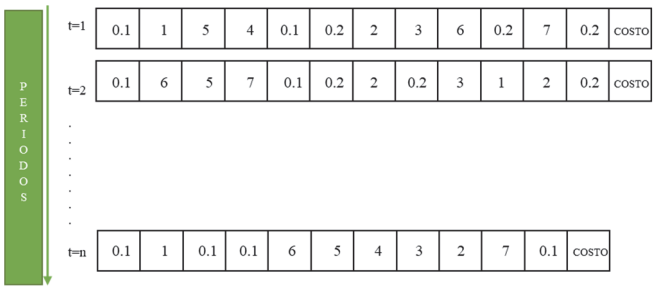

Fig. 5. Vector solución por periodos de planificación

Se usan las instancias de la literatura expuestas por [10], las cuales corresponden a un modelo IRP, y se ajustan incluyendo los costos de mantener inventario tanto en los clientes como en el proveedor, para intervalos de 5 hasta 50 clientes. Ahora bien, al ser este proyecto multidepósito multi-vehículo, se considera necesario realizar las siguientes modificaciones adicionales a las instancias:

- Se ubican los depósitos en coordenadas aleatorias pertenecientes a la posición de un cliente.
- No se dejan fijos, ni la cantidad de depósitos ni los vehículos asociados a los cientes, estos hace parte de la experimentación para observar la eficiencia de todas las posibles soluciones.
- Para generar el costo de transportar desde un punto i a j (CTij) se asocia al costo de transportar con una velocidad constantes sobre distancias euclidianas.

Y entonces sobre las anteriores, se realizan pruebas para una disponibilidad de máximo 3 depósitos por instancia para un horizonte de planificación de 3 períodos. La forma en que se expresa la estructura de los parámetros para cada una de las combinaciones posibles es la siguiente:

(# Iteraciones, # max de Vehículos disponibles, # depósitos Adicionales, # población Inicial).

Dado que las instancias escogidas provienen de un modelo con un único depósito, donde para este trabajo los depósitos adicionales se añadieron de manera aleatoria en alguna posición perteneciente a algún cliente, en la estructura del parámetro solo se verá reflejado la cantidad de depósitos adicionales, es decir, si la cantidad de depósitos totales es 3, en la estructura del parámetro aparecerá el valor de 2.

Las instancias se nombran para 5 clientes abs1n5 hasta llegar a la de mayor cantidad de clientes abs1n50, la forma de nombrar cada prueba consiste en incluir al final (. #prueba),

Estimating the Dynamic Impact of COVID-19 State-level Mobility Interventions in Brazil

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Abstract. The Social distancing and quarantine are considered the so far most effective policy to prevent an increasing contagion of COVID-19. While the economic impact from the implementation of this strategy is evident, empirical assessments to measure the disease outbreak's impact are still scarce. The first results reported in this assessment aim at quantifying this prospect. Data over time and over 27 Brazilian federations in 5 regions provided by Google's COVID-19 Community Mobility Reports and classified by place categories (Retail and Recreation, Grocery and Pharmacy, Parks, Transit Stations, Work-places, and Residences) are autoregressed on the COVID-19 incidence in Brazil using Generalized Linear Poisson Regression to measure the dynamic impact of mobility on each socioeconomic category. The assessment provides estimations for the time gap between contagion and data disclosure for public authorities' decision-making, first estimations regarding the propagation R_0 and R_0^+ in Brazil, and the mobility impact and marginal contribution for each place categories. The most critical cities in Brazil based on Optimized Hotspots Analysis are investigated with a brief discussion on the effects of population density and the Carnival in São Paulo and Rio de Janeiro. Suggestions for local planning based on the results are reported in conclusion.

Keywords: COVID-19, Mobility Interventions, Generalized Linear Estimations, Geographic Information Systems, Spatial Correlation, Contagion Mapping.

1 Introduction

Since the World Health Organization (WHO) announcement declaring the novel coronavirus outbreak a pandemic, Brazil has increased the number of confirmed cases. On February 26, 2020, the first case of the Severe Acute Respiratory Syndrome Coronavirus 2, aka COVID-19, was confirmed in São Paulo. Because of seasonal differences (e.g., winter compared to summer) and cultural differences (e.g., smoking habits), and because Brazil has a much bigger vulnerable population exposed to a wider set of tropical infectious diseases, resulting in a higher acquired immunity, many authorities had great expectations the outbreak would not be as aggressive

compared to Europe. The skepticism of public authorities on the outbreak proved wrong. No more than 93 days after the first case, the country reported 438,238 confirmed cases and 26,754 deaths, making Brazil the second country with the most confirmed cases in the world [1], [2], leading the World Health Organization to declare Brazil as the new epicenter of the coronavirus outbreak. In July, the country reached more than 1.8 million confirmed cases and more than 70 thousand deaths.

The outbreak brought many uncertainties about allocating hospitalization resources [3] economic prospects and intervention policies [4]. Social Distancing, Quarantine, and Isolation are assumed to be the most efficient strategies to reduce the exponential epidemic growth jeopardizing health systems in vaccines' absence. Most mobility sanctions and social distancing measures to combat the Coronavirus in Brazil began in the week from March 15 in several states. Gradually, schools and universities were closed, gyms, cinemas, theaters and museums opening were forbidden, civil servants and public employees moved to home office working and, in some localities such as São Paulo, retail and non-essential services were closed. Despite all efforts, the rate of social isolation has been below the ideal.

One of the many reasons is the Federal Government's recurrent position downgrading the benefits of state-level mobility interventions. According to Ajzenman, Cavalcanti & Da Mata [5], who investigated geographic location data from 60 million mobile phones combined with voting information of 2018 national elections, social distancing and quarantines are significantly reduced in pro-government localities after Brazil's president dismissing the risks associated with the COVID-19 pandemic and publicly and emphatically advise people to rebel against state mobility interventions.

Despite ongoing guidelines from the World Health Organization, scholars, scientists, and experts worldwide in order to contain an exponential spread, suggesting social isolation has been continuously dividing opinions around the world when they are weighted against economic prospects. The different interpretations of the current trade-off between economic development and the health systems' stability can be attributed to a lack of feasible evaluations. While the closing business impact is evident in the unemployment rate for many sectors of the economic activity, the mobility impact in the disease propagation is not as straightforward. This conflict of interest culminated in the minister of health's demission on April 16 and an unprecedented political crisis.

The first results reported in this research aim to contribute to this discussion, providing estimates for the dynamic mobility impact considering different economic place categories, estimates for the R0, and R0+ to aid policymakers' strategic planning. The spatial incidence in Brazil's most critical areas is investigated through optimized hot spots analysis, questioning the potential determinants and government responses to the crisis. The methodology and criteria associated with the model choice are described in the next section.

2 Methodology

There is an average time lag of three weeks from the initial contamination to the data curation and disclosure by health authorities in Brazil. This is because it takes from one to two weeks to manifest the most severe symptoms that would lead to testing, and from one to two weeks for the testing results. This reasoning has statistical support in this assessment. We have performed a series of modeling considering time lags of 1, 2 and 3 weeks for new and total cases and for the percentage mobility in six place categories: retail and recreation, grocery and pharmacy, parks, transit stations, workplaces or residences. Data were provided by Google [6] COVID-19 Community Mobility Reports and by Brazil [1] Ministry of Health epidemiological report. Georeferenced data at the federative level were obtained from Cota [7] COVID-19 repository.

Combining these variables in additive and multiplicative interactions for different probability distribution families (e.g. Gaussian, Gamma, Poisson) and different link functions (e.g. Identity, Inverse and Log) offered interesting results for choosing the most appropriate model. This choice was made based on three criteria: (1) statistical support, (2) parsimony and, (3) quality of data/parameters to the empirical knowledge. Models presenting 3 weeks time lag had a higher number of statistically significant variables and interactions (measured by the p-values). Parsimony, measured by the Akaike [8] Information Criterion (AIC), refers to the trade-off between representativeness and simplicity of a model. The third criterion is an assumption based on specialized knowledge in order to avoid poor quality inputs. General Linear Models with Poisson multiplicative interactions sustained the best adherence to these criteria.

Poisson regression models have been used to determine associations of the COVID-19 and environmental, meteorological and ecological factors, including population density, temperature, solar radiation, air quality and meteorological variables [9], [10], [11], [12], [13]. Zhang, Ma, and Wang [14] employed a segmented Poisson model to analyze the available daily new cases data of the COVID-19 outbreaks in the six countries, considering the governments' interventions (stay-at-home advises/orders, lockdowns, quarantines and social distancing). Agosto and Giudici [15], [16], investigated the contagion dynamics of the COVID-19, which can heavily impact health, economics and finance, using a Poisson model autoregressed on daily new observed cases. Furthermore, Ahmed [17] carried out studies using Poisson regression analysis to quantify patients' delays and the health system and identify their associated factors.

Autoregressed models with exogenous determinants are common for public policy, laws and sanctions evaluations [18]. Following a similar approach, and based on the decision criteria for choosing the most appropriate model, the number of new coronavirus cases is autoregressed to the number of new cases preceding 3 weeks and re-

gressed to the interaction of COVID-19 base (the total number of cases up to the 3 weeks lag) with the place mobility variables. Formally:

$$\ln \lambda_i = X\beta \;\; \therefore \;\; y_i = e^{X\beta} \,|y_i \sim Poisson\,(\lambda_i) \forall\, i = 1,2,3,\dots,n \qquad \textbf{(1)}$$

Where: $X\beta$ is the linear predictor $(b_0 + \prod_{j=1}^{7} b_j x_i)\, \forall\, i = 1,2,3,\dots,n$, with 120 multiplicative interactions, such that:

b_0 = coefficient for the effect of COVID-19 new cases 3 weeks before (the R_0^+)
b_1 = coefficient for the effect of COVID-19 cases reported 3 weeks before (the R_0)
b_2 = coefficient for the effect of retail and recreation mobility reported 3 weeks before
b_3 = coefficient for the effect of grocery and pharmacy mobility 3 weeks before
b_4 = coefficient for the effect of parks mobility reported 3 weeks before
b_5 = coefficient for the effect of transit stations mobility reported 3 weeks before
b_6 = coefficient for the effect of workplaces mobility reported 3 weeks before
b_7 = coefficient for the effect of residences mobility reported 3 weeks before

Low mobility levels is expected to have a positive effect on reducing disease propagation, considering the place categories. The log link function $(\ln \lambda_i)$ in the Poisson GLM is appropriate in this modelling for keeping non-negative the projection λ when the mobility regressors X or coefficients β is expected to have negative values. Likewise, higher mobility is expected to contribute to increasing transmission.

The week from March 14 was considered as a reference for counting the initial seed of cases. This is the week 15 from the 27 federations disclosed the first cases, and most of the state-level mobility sanctions were first implemented. The initial seed of cases works as a baseline to control the autoregressive covariate's empirical estimation in this dynamic relationship. In addition, it works to identify the first week of significant macro data to model the phenomenon. Some federations have cases prior to the designed initial week. The northern states of Pernambuco (2 cases on March 12), Rio Grande do Norte (1 case on March 13), Alagoas (1 case on March 08), and Bahia (1 case on March 06) are some instances. The bigger seed of initial cases is for São Paulo, which had their first case on February 26, away before any other federation, counting 56 new cases along the weeks until March 14, and 340 new cases in the first week from March 14, resulting in a seed of 396 initial cases.

3 Assessment and Discussion

Table 1 reports the main results. The coefficient sign represents the overall data relation of that specific base or place category with COVID-19 propagation (new cases). Two places categories exhibit a negative relation with COVID-19 (Retail and Recreation and Workplaces). This can be interpreted as a spurious correlation problem: the same weeks an aggressive mobility reduction was observed in business, civic and cultural activities due to sanctions aiming at closing malls, shops, commercial centers, theaters, stadiums, outdoor events, service units and public administrations

coincide with the COVID-19 exponential increase in Brazil. We cannot attribute, however, this increase to the mobility reduction in these places. This leads to believe correlation does not imply causation for these categories considering Brazil as a whole. This prospect may not be true for smaller disaggregated data on regions, states or municipalities.

Another evidence is the exponential coefficient for these places categories. The exponential coefficient (Exp. Coeff.) is a proxy for how much new cases respond, on average, to cases and to mobility changes three weeks before. The estimates for retail and recreation and workplaces are small (0.135 and 0.788, respectively) compared to other estimates such as transit stations (2.232) and residences (2.463), despite the very significant p-values. The very high exponential coefficient for Grocery and Pharmacy is another instance of spurious data correlation in this case. The same weeks supermarkets, grocery stores and pharmacies have experienced a considerable demand increase coincide with the COVID-19 exponential increase in Brazil. Nevertheless, we have no additional evidence to attribute COVID-19 exponential increase to the mobility increase in these places, leading to believe correlation does not imply causation for this category either, considering Brazil as a whole.

The exponential coefficients cannot be interpreted as additive predictors individually because of the multiple interaction modelling structures. Nevertheless, they provide a notion of overall importance each base or place mobility has on new cases of COVID-19. For a more empirical quantitative measure of the mobility impact, we provide the marginal contribution estimates. In this dynamic modelling, estimates for the R0, R0+ and for the mobility impact of each place category change along the time and along the regions and states. For each week and for each region we have a different marginal contribution. The marginal contributions reported in Table 1 are estimations for the individual effect of each variable on the number of new coronavirus cases from May 9 to May 16, 2020. These are obtained by adding one unit change to the base of cases (new cases or total) or by adding 0.001% mobility change to the place category (retail and recreation, grocery and pharmacy, parks, transit stations, workplaces or residences), keeping everything else constant, them investigating the potential increase or decrease in the prediction for COVID-19. Statistical support is measured by the p-values.

Table 1. Estimates for Brazil

AIC: 14313; Poisson (link = "log"); null dv.: 3229781 (173 df); res. dv.: 12680 (45 df); Fisher SI: 6; mult. interact. 120; min. dvrs.: -22.392; max. dvrs.: 34.825; 1q. dvrs.: -3.702; 3q. dvrs: 2.399; med. dvrs.: 0.018

Covariates	**Marginal Contribution [1] [2]**	**Exp. (Coeff.)**	**Coefficients**	**P-values [3]**
Covid-19 ($\mathbf{R_0}$)	0.9026342	2.1831049	7.807e-01	< 2e-16 ***
Covid-19 ($\mathbf{R_0^+}$)	7.49274	1.0020168	2.015e-03	< 2e-16 ***
Retail & Recreation	5.543848	0.1355574	-1.998e+00	< 2e-16 ***

Grocery & Pharmacy	-1.600595	19.7734385	2.984e+00	< 2e-16 ***
Parks	0.1696293	1.1263827	1.190e-01	0.012710 *
Transit Stations	0.7903152	2.2323520	8.031e-01	4.03e-12 ***
Workplaces	-3.774877	0.7883294	-2.378e-01	0.000103 ***
Residences	3.760099	2.4628843	9.013e-01	0.000437 ***

[1] Marginal Contribution (Impact) in the cases from May 9 to May 16, 2020 (third week of May).

[2] Estimates for a marginal increment of one additional COVID-19 case and 0.001% additional mobility.

[3] Significance Scores: '***' 0.001 ≤ p-value; '**' 0.01 ≤ p-value < 0.001; '*' 0.05 ≤ p-value < 0.01.

Estimates for the R0 and R0+ varies according to the week and region. For the third week of May we can assume each new case three weeks before was responsible, on average, for 7.49 new cases. The mobility increase in Grocery and Pharmacy and Workplaces had a negative effect on new cases, whereas the mobility increase in Retail & Recreation, Parks, Transit Stations and Residences had a positive effect. The positive effect of mobility changes in residential areas can be attributed to favelas and poor communities' vulnerability. Despite the pandemic, Baile funk parties, *peladas* (pick-up soccer games) and many other forms of social organization are reported in many peripheries and informal urban settlements.

Some estimates according to the different regions (north, northeast, center west, southeast and south) are reported in Tables 2, 3, 4, 5 and 6. Figures illustrate the spatial concentration. When disaggregating the country data into small datasets, there is a lack of significant sample for each region. Therefore, most estimation for the mobility impact and contagion does not have statistical support. For this reason, this information is omitted in the Tables. We expect to provide more comfortable estimates by integrating more massive datasets in the forthcoming months. The most significant impacts are mobility in workplaces for the southeast region, parks for the center-west, residential areas in the northeast and retail and recreation in the north region. The estimates refer to a 1% marginal change.

Figure 2. North

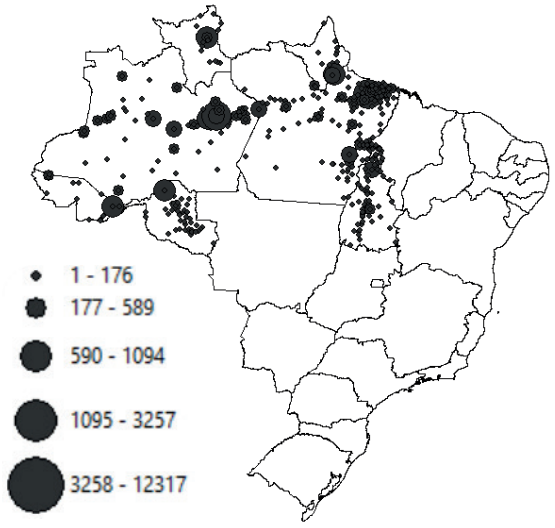


Table 2: Estimates for the North Region

AIC: 2411; Poisson (link = "log"); null dev.: 74461.6 on 40 df.; res. Dev.: 2049.2 on 18 df; fisher SI: 5

Covariates	Marginal Contribution	P-value
Covid-19 (R_0)	3.981363	< 2e-16 ***
Covid-19 (R_0^+)	-	-
Retail & Recreation	635.1778	< 2e-16 ***
Grocery & Pharmacy	-	-
Parks	-	-
Transit Stations	-	-
Workplaces	-	-
Residences	-	-

Figure 3. Northeast

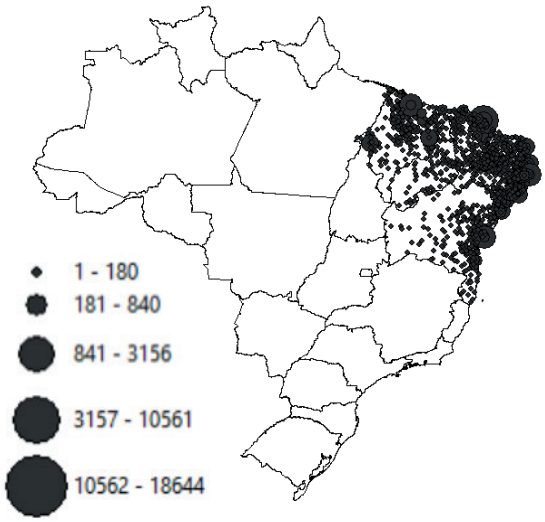


Table 3: Estimates for the Northeast Region

AIC: 585.69; Poisson (link = "log"); null dev.: 1.054e+06 on 58 df.; res. dev.: 2.921e-12 on 0 df; fisher SI: 3

Covariates	Marginal Contribution	P-value
Covid-19 (R_0)	0.7959314	< 2e-16 ***
Covid-19 (R_0^+)	1.000479	< 2e-16 ***
Retail & Recreation	27.84628	< 2e-16 ***
Grocery & Pharmacy	-	-
Parks	11.64888	< 2e-16 ***
Transit Stations	-	-
Workplaces	183.5822	< 2e-16 ***
Residences	301.5848	< 2e-16 ***

Figure 4. Central West

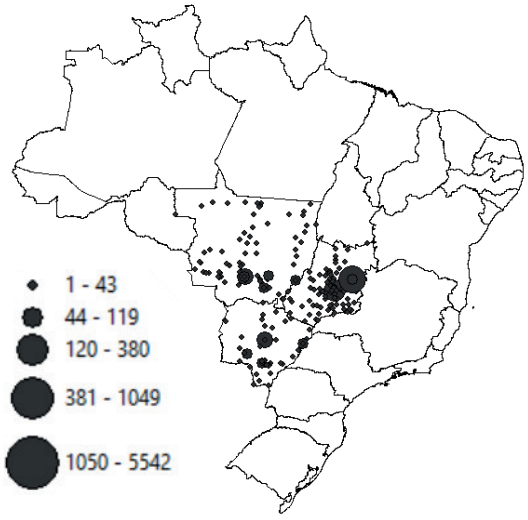


Table 4: Estimates for the Central West Region
AIC: 243.31; Poisson (link = "log"); null dev.: 7514.92 on 25 df.; res. dev.: 16.98 on 2 df; fisher SI: 4

Covariates	Marginal Contribution	P-value
Covid-19 (R_0)	-	-
Covid-19 (R_0^+)	-	-
Retail & Recreation	-	-
Grocery & Pharmacy	-	-
Parks	40.19183	0.0079 **
Transit Stations	-	-
Workplaces	-	-
Residences	-	-

Figure 5. Southeast

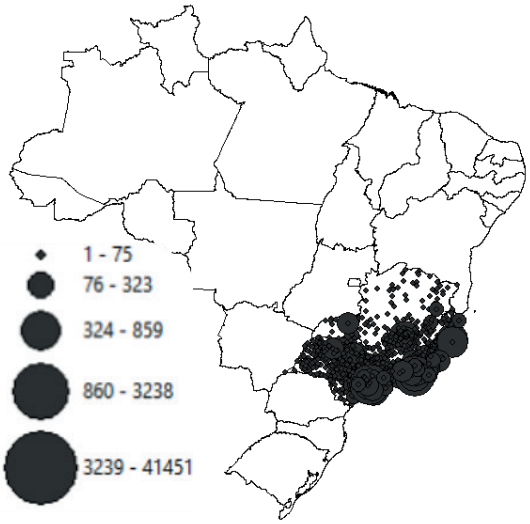


Table 5: Estimates for the Southeast Region
AIC: 655.84; Poisson (link = "log"); null dev.: 113107.42 on 27 df.; res. dev.: 351.29 on 4 df; fisher SI: 4

Covariates	Marginal Contribution	P-value
Covid-19 (R_0)	-	-
Covid-19 (R_0^+)	1.291627	< 2e-16 ***
Retail & Recreation	-	-
Grocery & Pharmacy	-	-
Parks	9.183066	< 2e-16 ***
Transit Stations	-	-
Workplaces	80.36371	< 2e-16 ***
Residences	-	-

Figure 6. South

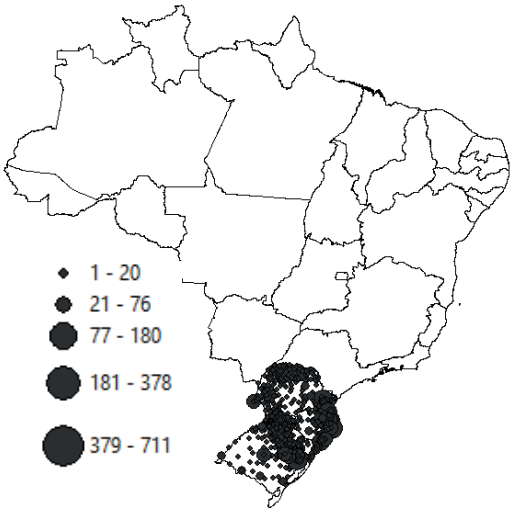


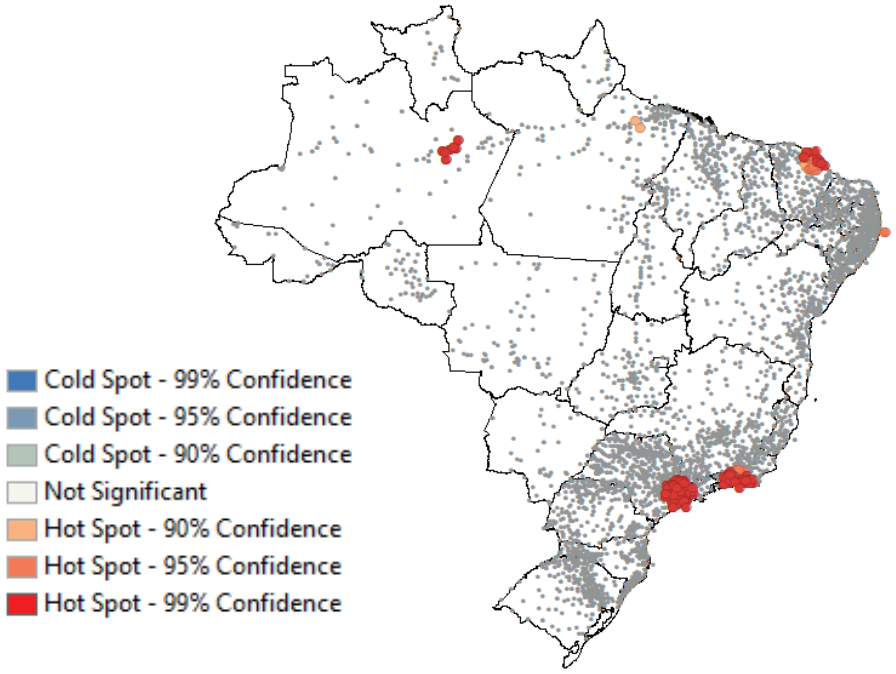
Table 6: Estimates for the South Region
AIC: 196.34; Poisson (link = "log"); null dev.: 4.7630e+03 on 19 df.; res. dev.: 6.4171e-14 on 0 df; fisher SI: 2

Covariates	Marginal Contribution	P-value
Covid-19 (R_0)	-	-
Covid-19 (R_0^+)	-	-
Retail & Recreation	-	-
Grocery &	-	-

Pharmacy		
Parks	-	-
Transit Stations	-	-
Workplaces	-	-
Residences	-	-

The most critical cities are evaluated using Optimized Hot Spots Analysis. This methodology offers Getis-Ord [19] statistic for each location that indicates where cities with either high or low COVID-19 cases cluster spatially. The objective is to assess the COVID-19 intensity through cities. We question whether potential mobility contributions to eventual hot spots could indicate a spatial concentration of municipalities composing the input features aggregating the COVID-19 occurrences. A similar analysis can be accessed in Menezes et al. [20] and Nepomuceno & Costa [21] investigating the spatial concentration of crime in the urban space. In this case, each of these geographic locations' total occurrences are the analyzed field in the analysis. Figure 7 presents the visualization.

Figure 7. COVID-19 Optimized Hot Spots in Brazil



The hot spot cluster for 99% confidence is composed of the metropolitan areas of the capitals Manaus in the north, Ceará in the northeast, São Paulo and Rio de Janeiro in the southeast. In addition to a great incidence, these cities are surrounded by other

cities of high COVID-19 incidence. The impact on the health system is summed to a higher probability of contagion in these areas, which makes this significant spatial association critical and requires urgent attention by the public authorities.

Rio de Janeiro and São Paulo have the second and third highest population density, and the fifth and second capitals with the highest population density. Ceará has the capital with the highest population density in Brazil. This information combined with the airline hubs for international flights in these capitals can explain, at least partially, the high initial incidence and fast spread of COVID-19.

Another factor that may explain the current critical scenario for those cities is originated in the Community Transmission and can related to the most popular Brazilian festival: the Carnival. Community Transmission is characterized when authorities are unable to trace the source of the infection. The states of São Paulo (SP) and Rio de Janeiro (RJ) have the first community transmission officially reported on March 13, which according to our specifications, can be traced back to the last week of February reserved to Carnival holidays. During the Carnival week, all places categories in São Paulo and Rio de Janeiro had a negative mobility change, with an exemption on Parks and Residential areas which are the places concentrating Street Carnival and parades.

4 Conclusion

Brazil's COVID-19 response has been one of the most controversial in the world. If by one hand state governments and municipalities efforts follow international protocols and recommendations, on the other, there is a big question about the federal administration's institutional preparedness, which constantly jeopardizes the prospects of mobility sanctions, social distancing, and quarantine campaigns. The first results reported in this assessment aim at contributing to this discussion. In particular, reducing mobility in residential areas and retail places is a challenge local authorities should prioritize due to their high potential. The absence of the state in favelas can make longer the trade-off between the economy and health. Unquarantine planning based on the individual impact of these place categories and the interaction with external localities can be an interesting avenue to anticipate developing the first communities free from the pandemic. Lastly, the question on model selection for the best representation of data is expected to be addressed with robust statistical tests in future works.

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Desenvolvimento de produto *Lean* e *Green*: um estudo comparativo entre PMEs Brasileiras e Japonesas

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Abstract. Com a Revolução Industrial, os processos de produção sofreram mudanças. Sendo assim, as empresas focaram no desenvolvimento de novos produtos, procurando obter maior rendimento com menos desperdícios, adotando práticas *lean*. Além disso, com o objetivo de produzir com consciência, adotaram práticas *green*. Com a aplicação de práticas *lean* e *green* as empresas conseguem reduzir a quantidade de resíduos, melhorar a utilização de recursos e aumentar a competitividade. Para as PMEs a aplicação desses conceitos é mais complexa, devido à quantidade limitada de recursos disponíveis. O objetivo desse trabalho é analisar a maturidade das metodologias *lean* e *green* no processo de desenvolvimento de produtos em PMEs brasileiras e japonesas. A metodologia é multicriterial, aliando o método Processo de Análise Hierárquica (fase 1- priorização de critérios) e TOPSIS 2-*Tuple* (fase 2 – hierarquização das 18 facilitadores *lean-green*). A pesquisa compreende três PMEs japonesas e três brasileiras, do setor metalmecânico e com foco no desenvolvimento de produto. Os resultados esperados para o método TOPSIS 2-*Tuple* são que o contexto japonês esteja com as metodologias *lean* e *green* mais avançadas que o contexto brasileiro, visto que foi onde surgiu a metodologia *lean* e está sendo utilizada há mais tempo, permitindo maturidade maior nas empresas. O método AHP (fase 1 da pesquisa) quando aplicado com especialistas dos dois países apresentou divergência de hierarquização sobre quais as características mais relevantes nas empresas. Para os japoneses, a incidência de inovação é a característica principal, já para brasileiros, a característica mais determinante é o domínio da alta gerência nos processos.

Keywords: Desenvolvimento de Produtos *Lean,* Desenvolvimento de Produtos *Green,* Desenvolvimento de Novos Produtos

1 Introdução

No século XVIII, com a Revolução Industrial, os processos produtivos deixaram de ser manufaturados para se tornarem fabris [39]. Com esse novo paradigma produtivo aumentou a competitividade entre as empresas. Para suprir as necessidades e visando conquistar mercado consumidor, as empresas foram obrigadas a passar por fases de inovação bruscas. Isso ocorreu, pois a vantagem competitiva está ligada à necessidade das empresas inovarem e aprenderem com a inovação [37].

Para conseguir conciliar a evolução, oriunda da revolução, com os restritos recursos é importante que eles sejam bem aproveitados, de maneira a obter rendimento máximo [8]. Tendo em vista esses aspectos, o desenvolvimento de novos produtos (NPD) está atrelado ao conceito de que se deve produzir com consciência, satisfazendo as necessidades dos clientes no presente, porém sem comprometer a capacidade de recursos para as gerações futuras suprirem as delas [30].

Para que o uso desses recursos ocorra de forma harmônica, há pilares sociais, econômicos e ambientais que balizam o desenvolvimento de produtos de uma forma sustentável. Ainda, é importante atentar-se ao fato que a sustentabilidade é um processo iterativo, o que implica em várias perspectivas e disciplina para sua aplicação e manutenção no médio e longo prazo [9].

Tendo em vista a quantidade limitada de recursos naturais, as empresas devem prezar para que todo o recurso disponível na empresa seja bem utilizado, evitando todo tipo de desperdício. Nesse sentido, para atingir o objetivo de maior rendimento com menos desperdícios, as empresas passaram a adotar o conceito de *Lean Manufacturing* (produção enxuta), tendo como origem o Sistema Toyota de Produção. Os princípios *Lean* são amplamente disseminados como meio para a eliminação de resíduos, proposição de valor e melhoria contínua no desenvolvimento de produtos [23].

Conforme exposto, para que as empresas tenham bom desempenho no campo de desenvolvimento de produtos, faz-se necessário o conhecimento e aplicação de métodos sustentáveis e de produção enxuta. De acordo com Oliveira [30] o NPD apresenta um conjunto de operações que influencia nos processos de manufatura, ciclo de vida dos produtos e adoção dos aspectos *lean* e *green* nas empresas.

O desenvolvimento de produto, atualmente, não se restringe apenas à funcionalidade técnica, mas sim equilibrando conceitos sustentáveis e enxutos como forma de garantir o crescimento da empresa e a manutenção dela no mercado [14]. Com base nos princípios do *lean* e do *green*, o NPD deve reduzir a quantidade de resíduos nas empresas, visando melhor utilização dos recursos produtivos [17] para aumentar a competitividade da empresa frente ao mercado. Além disso, o desperdício de recursos pode comprometer os aspectos financeiros das empresas [13].

Os facilitadores do *lean* e do *green* apresentam importância estratégica no NPD, uma vez que ambos os conceitos são aplicados visando reduzir custos, contribuir para a otimização e alcançar a sustentabilidade. Apesar dessa sinergia encontrada entre os conceitos, há uma lacuna na literatura onde a maioria dos estudos encontrados concentram-se em estudar o desenvolvimento individual de produtos com foco no *green* ou no *lean* [21]. Ainda, facilitam a alta competitividade da empresa no mercado [18]. Por fim, a literatura apresenta poucos estudos sobre o NPD em PMEs, gerando questionamentos sobre os processos de desenvolvimento de produtos que foram desenvolvidos e formalizados para empresas de grande porte, se podem ser transferíveis para pequenas empresas sem perdas [22].

O presente trabalho tem por objetivo analisar qual o nível de maturidade se encontram as PMEs avaliadas nas metodologias *lean* e *green* em dois contextos distintos (Brasil e Japão), além de encontrar quais os facilitadores desses conceitos que são realmente aplicados nas PMEs. O estudo tem duas fases, sendo que nesse artigo é

apresentada a fase 1- priorização de critérios para PMEs, sendo que a fase 2 está em fase de coleta e estará finalizada para a versão estendida após a realização do evento.

2 Referencial Teórico

O desenvolvimento de novos produtos (NPD) consiste em um conjunto de atividades, a partir das quais é possível exprimir as necessidades do mercado e dos clientes, fazendo um de tecnologias e estratégias competitivas. Ainda, está envolvido com todo o ciclo de vida do produto, desde a concepção do projeto até a descontinuidade dele no mercado [10], [22] e [33].

A introdução de novos produtos no mercado é a inovação pura [26]. Essa inovação é vital para o crescimento econômico das empresas, bem como para a formação de novas plantas e para o enfrentamento de novos desafios [40]. Além disso, para aumentar a competitividade e alcançar melhoria em termos de custo, qualidade e tempo, diferentes conceitos de gerenciamento foram estabelecidos na prática comercial [10]. Dentre esses conceitos estão as metodologias *lean* e *green*.

O *lean* enfatiza o desperdício em operações que não agregam valor aos produtos, enquanto o *green* objetiva seleção de materiais e a maximização do seu uso, como boas práticas de reutilização e reciclagem [18]. Apesar de poucos estudos conciliarem a implementação prática dos conceitos *lean* e *green* simultaneamente no desenvolvimento de produtos, ambos têm semelhanças de interesses e podem apresentar sucesso maior se aplicados em conjunto.

O *lean* é uma filosofia que define os meios para melhorar a otimização do sistema de produção [38]. Os princípios do *lean* são amplamente disseminados e aplicados como forma de eliminar resíduos, proposição de valor e melhoria contínua no processo de NPD [24]. Essa aplicação do *lean* no NPD foi nomeado de Desenvolvimento de Produtos *Lean* (LPD).

As empresas que adotam o LPD buscam eficiência e eficácia. A eficiência é buscada minimizando a variabilidade interna e externa e reduzindo todas as formas de desperdício nos fluxos de informação e produção. Já a eficácia é obtida aumentando a qualidade e o valor do produto sob a perspectiva do cliente [25]. Algumas práticas *lean* que potencializam o NPD, são: engenharia simultânea, modularização, envolvimento cliente e fornecedor e design para capacidade de fabricação. Essas práticas podem melhorar o processo de NPD e auxiliar no gerenciamento do portfólio de produtos [23].

Atualmente, as empresas buscam atingir seus objetivos no NPD não apenas por meio de processos eficientes, mas também mais produtivos e com operações sustentáveis. Essa busca por operações sustentáveis surgiu motivada, pela escassez de recursos, pressão internacional e órgãos nacionais adotando regulamentos ambientais [35].

Dessa forma, para um empresa ser *green,* ou seguir a linha de desenvolvimento de produtos *green* é simultaneamente uma oportunidade e uma necessidade [7]. Os principais objetivos do design sustentável de produtos são a redução do uso e emissão de recursos de um produto para o meio ambiente, bem como melhorar o desempenho socioeconômico ao longo do ciclo de vida do produto [11].

Dessa forma, o desenvolvimento de produtos *green* (GPD) deve contemplar uma abordagens na inovação, estratégias sustentáveis e metas e a incorporação formal de requisitos ambientais e por fim implementando ferramentas sustentáveis e personalizadas, além de integrar aspectos ambientais no gerenciamento de projetos [2].

A orientação para sustentabilidade pode ser incorporada pelas PMEs através do conhecimento associado ao nível de experiência e capacidade, tanto no aspecto estratégico como operacional [19].

As pequenas e médias empresas (PME) representam parte substancial da atividade econômica, em termos de números de empresa e do produto interno bruto (PIB) em praticamente todos os países do mundo [1]. No Japão, as PMEs representam cerca de 99,7% de todas as empresas, compondo 70,2% dos empregos e seus funcionários constituem 80% dos eleitores do país [6]. Já no Brasil as PMEs são responsáveis por, aproximadamente 60% da força de trabalho e 42% da massa salarial [4].

3 Metodologia

A pesquisa é delimitada a dois contextos distintos: PMEs do Japão, representando os países desenvolvidos e do Brasil, representando os países em desenvolvimento. As PMEs escolhidas apresentam atividade de NPD no setor metal mecânico em seus processos fabris.

Para o embasamento teórico foi realizado uma revisão sistemática da literatura, apoiada no método *Proknow-C* que foi desenvolvido para analisar quantitativamente artigos com prestígio científico. Esse método permite encontrar um portfólio relevante e alinhado com os eixos de pesquisa [43].

Durante a revisão, foram buscados artigos que tivessem relação com os eixos temáticos da pesquisa: *lean*, *green*, Pequenas e Médias Empresas e Desenvolvimento de Novos Produtos. Dentro desses eixos estão as palavras chave que foram buscadas nas bases científicas: *Green, Sustainable, Environment, Ecodesign, Lean, Kaizen, Six Sigmas, SME, Small and medium enterprises, Japanese small and medium enterprises, Developing Countries x Developed Countries, New product development, Product design, Comparative studies*. Todas as palavras chave foram escritas em inglês para que retornassem mais artigos sobre o assunto. A combinatória de palavras-chave a serem pesquisadas foi a permutação entre as palavras de todos os eixos de pesquisas, utilizando "*and*" entre as palavras de eixos distintos.

Para a busca pelos artigos foram utilizadas as bases científicas *Scopus* e *Science Direct* e delimitado a pesquisa entre os anos de 2014 a 2019, visando obter apenas artigos com informações atuais, visto que essa pesquisa iniciou em março de 2019, porém com uma margem de cinco anos para que a quantidade de documentos encontradas seja relevante para a realização do estudo. Como resultado final da pesquisa, foram selecionados 18 artigos, conforme pode ser conferido na Tabela 1. Esse portfólio bibliográfico permitiu que fossem definidos os critérios (características das PMEs) e as alternativas (facilitadores do *lean-green*), além de auxiliar no embasamento para conhecer as metodologias aplicadas nessa pesquisa.

Tabela 1 – Portfólio de Pesquisa

Título	Autores
Extracting key factors for sustainable development of enterprises: Case study of SMEs in Taiwan	Matinaro, Ville; Liu, Yang; Lee, Tzong-Ru (Jiun-Shen); Poesche, Jurgen
Sustainable product design and development: A review of tools, applications and research prospects	Ahmad, Shamraiz; Wong, Kuan Yew; Tseng, Ming Lang; Wong, Wai Peng
Lean and *green* approach: An evaluation tool for new product development focused on small and medium enterprises	Oliveira, Gilson Adamczuk; Tan, Kim Hua; Guedes, Bruno Turmina
A framework for selecting *lean* practices in sustainable product development: The case study of a Brazilian agroindustry	Lermen, Fernando Henrique; Echeveste, Márcia Elisa; Peralta, Carla Beatriz; Sonego, Monique; Marcon, Arthur
Proposal of a novel reference system for the *green* product development process (GPDP)	de Medeiros, Janine Fleth; Lago, Nicole Cecchele; Colling, Camila; Ribeiro, José Luis Duarte; Marcon, Arthur
A generic framework to support the implementation of six sigma approach in SMEs	Deeb, Salah; Haouzi, Hind Bril-El; Aubry, Alexis; Dassisti, Michele
Lean product development and *lean* manufacturing: Testing moderation effects	Marodin, Giuliano; Frank, Alejandro Germán; Tortorella, Guilherme Luz; Netland, Torbjørn
Lean Product Development for Small and Medium-sized Suppliers	Dombrowski, Uwe; Karl, Alexander
The Way from *Lean* Product Development (LPD) to Smart Product Development (SPD)	Rauch, Erwin; Dallasega, Patrick; Matt, Dominik T
Classification of micro, small and medium enterprises (M-SME) based on their available levels of knowledge	López-Ortega, Eugenio; Canales-Sanchez, Damian; Bautista-Godinez, Tomás; Macias-Herrera, Santiago;
Does Kaizen create backward knowledge transfer to Southeast Asian firms?	Machikita, Tomohiro; Tsuji, Masatsugu; Ueki, Yasushi
Barriers in *green lean* six sigma product development process: An ISM approach	Kumar, S; Luthra, S; Govindan, K; Kumar, N; Haleem, A
New product development in knowledge-based manufacturing SMEs active in the ICT industry: A conceptual framework	Meigounpoory, M R; Jozani, M M
Optimising NPD in SMEs: a best practice approach	Leithold, N; Woschke, T; Haase, H; Kratzer, J
The role of competitive strategies on export market selection by SMEs in an emerging economy	Ayob, A H; Senik, Z C
Small and medium enterprises' collaborations with universities for new product development: An analysis of the different phases	Buganza, T; Colombo, G; Landoni, P
Exchange of Knowledge in Customized Product Development Processes	Klein, Patrick; Pugliese, Dante; Lützenberger, Johannes; Colombo, Giorgio; Thoben, Klaus-Dieter
Technique and system: The spread of Japanese management techniques to developing countries	Kaplinsky, Raphael

Fonte: Autores

A ideia central a ser desenvolvida nesse trabalho é analisar o quão aplicados estão os princípios das metodologias *lean* e *green* nas PMEs japonesas e brasileiras, analisando quais são os facilitadores mais utilizadas e eficientes para atingimento da maturidade das empresas nesses conceitos dentro do NPD. A coleta de dados nos dois países serve como base para comparação do desenvolvimento deles.

Essa análise irá ocorrer fazendo uso de metodologia multicriterial. Serão aplicados dois métodos multicriteriais combinados: AHP (fase 1) e TOPSIS 2-*Tuple* (fase 2). Esses métodos servem de auxílio na tomada de decisões. Eles possuem etapas genéricas, na qual constam a escolha dos critérios de avaliação, alternativas sobre os

critérios de avaliação, analisar e definir qual a melhor alternativa, sendo ela a mais próxima do ideal [31].

A metodologia de coleta de dados acontecerá em duas etapas distintas. Sendo que, a primeira inclui entrevista com os especialista em PMEs para atribuição dos pesos de cada um dos critérios, hierarquizando as características mais relevantes. Os dados serão coletados a partir de uma planilha eletrônica. A segunda etapa, consiste na entrevista com as pessoas responsáveis pelo NPD nas PMEs selecionadas para o estudo. Nessa etapa serão relacionados cada uma das alternativas (facilitadores do *lean* e do *green*) com os critérios (características das PMEs), atribuindo graus de aplicabilidade dentro da empresa. Os dados nessa fase da pesquisa serão coletados a partir do uso de formulários eletrônicos.

Os critérios representam as características das PMEs, buscados na literatura [12], [29], [30] e adaptados ao contexto o qual busca-se compreender: 1 – Flexibilidade (Estrutura e fluxo de informações flexíveis, resposta rápida às mudanças ambientais, plana com poucas camadas de gerenciamento, resistência insignificante à mudança, alta gerência próxima ao ponto de entrega e muito visível, proporcionando mudanças rápidas, se necessário), 2 – Dificuldade no NPD (Falha em compreender a importância do projeto do produto e baixo grau de formalização), 3 – Inovação (Alta incidência de inovação e criatividade individual incentivada), 4 – Recursos limitados (Pessoas, tempo para realizar inovação e financiamento limitados), 5 – Autoridade (Gerente comandando todas as atividades da empresa sem conhecimento adequado).

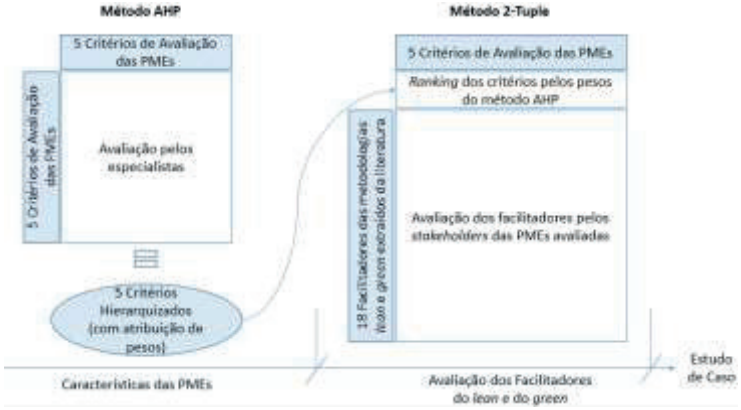
As alternativas são os facilitadores do *lean* e *green* buscadas na literatura [30], sendo elas: Melhoria Contínua (A forma como as melhorias ocorrem não deve ser abrupta e pontual, mas sim longitudinal e gradativa), Transferência de conhecimento entre projetos (As equipes podem usar a experiência acumulada das melhores práticas de projetos anteriores para projetar novos produtos), Definir Valor e Fluxo de Valor (No NPD, iterações sucessivas e coordenadas se traduzem em valor. O mapeamento de fluxo de valor é um método de sucesso aplicado em pequenas empresas), Ferramentas de ecodesign e capacidade dinâmicas (design para o meio ambiente, eliminação de resíduos e recursos dinâmicos verdes), Conhecimento e Aprendizagem (Conhecimento e aprendizagem estão associados à capacidade das organizações de reter conhecimento tácito para aplicá-lo em suas operações de NPD), Avaliação do Ciclo de Vida (Integra as questões ambientais com os efeitos dos produtos, desde a fabricação até o descarte final, Seleção de materiais (Consequências de uma correta determinação dos materiais influenciam as operações de reciclagem e descarte no ambiente natural), Padronização de Processos (Consiste em padronizar todas as atividades periódicas), Gestão da variedade de produto (Consiste na padronização de peças, módulos e subconjuntos), Prototipagem rápida, avaliações e testes (Usada para validar tanto os problemas geométricos quanto os modos de falha de alguns componentes), Controle Baseado em Conjuntos (No controle do plano baseado na responsabilidade individual, os gestores definem os marcos, enquanto a equipe do projeto é autônoma para programar seus fluxos de trabalho, estimar a duração das atividades e dar feedback aos gestores sobre a viabilidade da proposta horários), Engenharia Baseada em Conjuntos (Considera conjuntos de projetos e soluções ao longo do desenvolvimento, descartando, sob múltiplos critérios, aquelas soluções que são inferiores às demais), Engenharia

Simultânea (As etapas do NPD são executadas sequencialmente, sendo que a próxima etapa inicia antes do término da atual), Especialização de Engenharia e Nivelamento de Carga de Trabalho (Os engenheiros da equipe do projeto devem permanecer em suas áreas de especialização), Integração de Fornecedores (Os fornecedores estão ligados à equipe do projeto), Gerente de Projetos Forte (O engenheiro chefe é o responsável pela definição do valor), Redução de Resíduos (Melhor aproveitamento dos recursos), Análise de Impactos Ambientais (Analisa os materiais utilizados no desenvolvimento do produto, de forma que não apresentem nenhum risco ambiental quando forem descartados ao final de sua vida útil).

O presente trabalho tem como base o artigo elaborado por Oliveira *et al.* [30]. As alternativas passaram por um refinamento de acordo com a mudança de cenário e a perspectiva do estudo comparativo. Os critérios também foram refinados e são alternados entre critérios de custo, aqueles que tem característica negativa e critérios de benefício, que possuem características positivas.

A Figura 1 apresenta a fase multicritério, na qual são desenvolvidos os métodos AHP para determinação dos pesos dos critérios de avaliação das PMEs e o método de variável linguística TOPSIS 2-Tuple, no qual a alta direção ou o responsável pelo NPD da empresa avaliam o quanto os facilitadores listados estão implantados nas PMEs.

Figura 1 - Modelo de avaliação para as operações de NPD nas PMEs.



Fonte: Adaptado de Oliveira [30]

No método AHP é feita a comparação dos critérios aos pares. Os elementos a serem comparados são dispostos em uma matriz *n*x*n* onde serão realizadas as correspondências. Na diagonal principal os elementos são iguais a um e os outros são recíprocos das comparações iniciais.

As comparações devem seguir a escala de Saaty [36] na qual, 1 significa que ambos elementos apresentam contribuição idêntica, 3 significa um julgamento levemente superior para um critério, 5 significa julgamento fortemente a favor de um critério, 7 significa dominância reconhecida de um critério e por fim, 9 significa dominância comprovada de um critério. Além disso tem os valores intermediários: 2, 4, 6 e 8 que podem ser utilizados caso haja a necessidade.

Para a atribuição de pesos para cada um dos critérios serão convidados especialistas da área do próprio país onde ocorrerá a pesquisa, Brasil e Japão, os quais deverão fazer a análise de prioridade utilizando o método de Processo de análise hierárquica, do inglês *Analytic Hierarchy Process* (AHP). O método AHP é considerado um método de seleção e tem como objetivo escolher em forma de hierarquia as alternativas apresentadas. A análise das alternativas ocorre par-a-par, elencando qual a melhor entre duas alternativas e quanto melhor uma que a outra. Esse método é realizado por especialistas do assunto em construir hierarquia através das respostas de especialistas, definir prioridades e verificar a consistência lógica das respostas [36].

Após a utilização do método AHP para a atribuição de pesos aos critérios acima listados, será aplicado o método de decisão multicritério de variáveis linguísticas. Esse segundo método a ser utilizado servirá para informar o grau de aplicabilidade de cada princípio nas PMEs. Esse método apresenta bons resultados para modelar e gerenciar incerteza e implica na realização de processo fazendo uso de palavras [27]. É uma ferramenta importante e que pode ser aplicado em problemas de diversas áreas para abordagem qualitativa, como recuperação de informações [15].

Porém, Herrera *et al*. [15] apresentam que se deve atentar para os termos linguísticos utilizados para que sejam simétricos, apropriados e cordiais para a aplicação. Ainda aborda sobre a grande abrangência do método que é tido como ponto forte, mas requer atenção, visto que a abrangência é muito mais que em métodos qualitativos.

Após a coleta de dados com as variáveis linguísticas, para que seja feita a análise e para facilitar os cálculos, os parâmetros linguísticos serão transformados em valores numéricos. Porém, logo após a análise, os valores são expressos de maneira linguística novamente.

O primeiro passo para a análise dos dados obtidos é estabelecer o conjunto de termos linguísticos que serão utilizados no processamento das informações. Depois, converter as variáveis linguísticas no equivalente de informação. Então é necessário identificar as soluções positivas e negativas ideais, para calcular a distância entre as alternativas até as soluções negativas e positivas ideais. Seguindo deve-se calcular a semelhança com a solução positiva ideal, calcular a variável linguística correspondente, com base no passo anterior e por fim, classificar em ordem das variáveis linguísticas.

O modelo linguístico conhecido como 2-tuple é representado na forma (s, $\propto$), onde s é um rótulo linguístico e $\propto$ é um valor numérico que representa um valor. Ainda, na questão de nomenclatura, β é o resultado de uma agregação dos índices de um conjunto de rótulos avaliados de termos linguísticos S [16].

A principal vantagem dessa representação é ter um domínio contínuo, sendo possível expressar qualquer informação no universo do discurso [44]. Para cada termo linguístico é necessário que haja um número difuso agregado [20].

Os stakeholders serão questionados através da entrevista estruturada. Para os critérios de benefício as perguntas serão da forma: “Considerando as práticas atuais em sua empresa: Qual a importância do facilitador “A1” na característica “C1” da empresa?”. Já, para os critérios de custo, as perguntas serão na forma: “Considerando as práticas atuais em sua empresa: Qual a importância do facilitador “A1” para reduzir os efeitos da característica “C2” da empresa?”.

O primeiro passo para a aplicação desse método foi estabelecer um conjunto de termos linguísticos para serem utilizados nos processamentos das informações. Tendo em vista que $S = \{s_0, \dots, s_g\}$, que $\Delta(\beta) = (S_i, \alpha)$, com $\alpha = \beta - i$ e $\alpha \in [-0{,}5, 0{,}5)$ e que $\Delta^{(-1)}(S_i, \alpha) = i + \alpha = \beta$.

Sendo que para representar cada um desses parâmetros linguísticos serão utilizados números difusos triangulares, do tipo fuzzy $\tilde{x}ij = (aij, bij, cij)$. Dessa forma, teremos as representações conforme Tabela 2:

Tabela 2 - Variável Linguística e equivalente Fuzzy

Variável Linguística	**Número *Fuzzy***
Nenhuma	0,00; 0,00; 0,17;
Muito Baixa	0,00; 0,17; 0,33;
Baixa	0,17; 0,33; 0,50;
Média	0,33; 0,50; 0,67;
Alta	0,50; 0,67; 0,83;
Muito Alta	0,67; 0,83; 1,00;
Absoluta	0,83; 1,00; 1,00;

Fonte: Autores

Após a atribuição de números difusos, eles serão normalizados para que após seja seguido o passo a passo conforme descrito acima.

Realizado a hierarquização das variáveis linguísticas para os dois casos analisados: Brasil e Japão, será realizada um estudo comparativo dos resultados de ambos para que seja possível encontrar as lições aprendidas de cada um dos países.

Os estudos comparativos ocupam lugar de destaque em pesquisas científicas, pois auxiliam em diagnósticos de problemas sociais, para o desempenho de políticas públicas e ao mesmo tempo, como parâmetro de referência para fonte de legitimação [32].

Os países, objetos de estudo, encontram-se em cenário totalmente diferentes e, analisar o nível de aderência, ou maturidade, das metodologias *lean* e *green* em cada um deles, permite que sejam observados pontos de melhorias e qual o grau de formalização do NPD nas PMEs desses países.

Para que a comparação entre dois países tão distintos ocorra de forma científica e seja, de fato, válida, as empresas escolhidas para esse trabalho atendem aos mesmos requisitos: todas as empresas classificam-se como PMEs, atuam no NPD do setor metal mecânico e utilizam potencialmente as metodologias *lean* e *green* em seus processos.

A escolha dos países para fazer parte dessa pesquisa aconteceu levando em consideração a importância de analisar cenários distintos e que se encontram em realidades econômicas diferentes para obter melhores resultados. Sendo assim, foi escolhido um país desenvolvido, o qual é o berço da metodologia *lean*, destaque em exportações e está localizado nas primeiras posições entre os países com o maior PIB: o Japão. Já o segundo país escolhido pertence à classe de países em desenvolvimento, está em constante ascensão para entrar no *ranking* de melhores PIBs e, por isso é conhecido como uma potência emergente: o Brasil.

A comparação entre os dois cenários relata tanto as diferenças quanto as semelhanças dos países estudados. Para isso, foram avaliadas e comparadas as respostas da pesquisa estruturada caso a caso, com o intuito de debater quais os facilitadores mais utilizados nas PMEs e quais as lições aprendidas das empresas Japonesas podem auxiliar as PMEs brasileiras a melhorarem o processo de NPD e aumentar o nível de aplicação e maturidade das metodologias *lean* e *green*.

Para realizar essa comparação de modo que todas as semelhanças e diferenças das empresas sejam abordadas com clareza, foi utilizado o método de escrita ponto por ponto, no qual são alternados pontos sobre um contexto e outro. Esse método permite que sejam comparadas diretamente as PMEs abordadas e possibilita que sejam discutidas todas as perguntas do questionário, avaliando as respostas de cada uma [32].

4 Resultados Preliminares e Discussão – fase 1

Esse trabalho é um refinamento de Oliveira *et al.* [30], o qual realizou uma análise da maturidade e aplicabilidade dos facilitadores do *lean* e do *green* nas PMEs brasileiras.

Os resultados esperados para essa pesquisa é que as empresas brasileiras apresentem um nível semelhante de adesão. Contudo, estima-se que haja um aumento da aplicabilidade dos facilitadores, uma vez que essas duas metodologias estão sendo cada vez mais difundidas recentemente. Já para as empresas japonesas, estima-se que o nível de aderência delas nas metodologias avaliadas seja mais elevado, uma vez que o Japão pode ser considerado o berço da metodologia *lean*. Conforme comentado anteriormente, os estudos comparativos ocupam lugar de destaque em pesquisas científicas, pois auxiliam em diagnósticos de problemas sociais, para o desempenho de políticas públicas em especial que possam ser avaliadas no contexto brasileiro.

Como refinamento para o trabalho elaborado por Oliveira *et al.* [30] apresenta-se os seguintes pontos: aumento de dois facilitadores relacionadas com a metodologia *green*, com o objetivo de equalizar a quantidade de facilitadores dos princípios *lean* e *green*; agrupamento de dois critérios com objetivos e definições semelhantes, tornando assim apenas cinco os critérios com características das PMEs; mudança dos métodos multicritérios utilizados, sendo que no trabalho de Oliveira *et al.* [30] foram utilizados AHP combinado com *Fuzzy*-TOPSIS e nesse trabalho são combinados os métodos AHP e TOPSIS *2-Tuple*. Essa troca ocorreu pois, o método TOPSIS 2-*Tuple* tem grande abrangência nas respostas, permitindo que por meio dele sejam gerenciadas as incertezas fazendo um de termos linguísticos, pode ser aplicado em várias áreas para a abordagem qualitativa, como forma de recuperação de informações [16]. Por fim, em Oliveira *et al.* [30] foi analisado o nível de maturidade das PMEs brasileiras nas metodologias *lean* e *green* e nessa pesquisa agrega-se o estudo comparativo em PMEs brasileiras e japonesas.

O instrumento e protocolo para coleta dos dados será o mesmo para ambos os países. Para o método AHP foi utilizada uma planilha eletrônica enviada aos especialistas em PMEs. Ao final do preenchimento da planilha os pesos para cada um dos critérios é calculado automaticamente. Os respondentes dessa etapa do processo são pessoas com conhecimento do contexto de PMEs, sendo que parcialmente é composto por diretores

executivos (do Inglês, Chief Executive Officer – CEO) de pequenas ou médias empresas renomadas no ramo que atuam e parcialmente é composto por professores estudiosos do assunto.

Para cada um dos países foram selecionados três especialistas em PMEs para responder a planilha responsável pela atribuição de pesos aos critérios. As qualificações de cada um dos especialistas podem ser observadas na Tabela 3 Dessa forma, foram coletadas ao todo seis respostas distintas dos especialistas que serão compiladas como forma de uniformizar o peso de cada critério, fazendo com que a métrica utilizada para posteriormente analisar os facilitadores do *lean* e do *green* nas empresas seja a mesma em ambos os países.

Tabela 3 - Especialistas e qualificações

Especialistas	Descrição das qualificações
E1 - Japão	Diretor de área de uma instituição governamental (Organização para PMEs)
E2 - Japão	Atualmente, na área acadêmica. Ex-banqueiro com anos de experiência com PMEs locais, agora CEO de uma construtora de médio porte.
E3 - Japão	Ex-CEO, com anos de experiência, de um fabricante de pequeno-médio porte.
E4 - Brasil	Analista técnica do SEBRAE atuando em programas e projetos de atendimento às pequenas e médias empresas
E5 - Brasil	Atua na área acadêmica. Pesquisadora de gestão estratégica para PMEs
E6 - Brasil	Atua em empresas e na academia. Contadora focada em administração de empresas e competitividade no mercado

Fonte: Os autores.

Na sequência, para a aplicação do método TOPSIS 2-*Tuple* (fase 2) serão utilizados formulários eletrônicos. Para cada um dos cinco critérios será elaborado um formulário distinto, sendo que todos eles apresentam o critério, a descrição e significado dele, bem como os facilitadores das metodologias *lean* e *green* e as descrições delas. Sendo organizados dessa maneira, são cinco formulários composto por 18 questões em cada um deles. As questões deverão ser respondidas de acordo com as práticas atuais dentro das empresas, para com isso validar o objetivo da pesquisa.

A coleta desses dados e o contato serão realizados por um pesquisador residente do país, tanto nas PMEs japonesas quanto nas brasileiras. Além disso, os formulários disponíveis para responder são no idioma do país em que está sendo aplicado para evitar que sejam respondidos níveis de aplicabilidade medianos por falta de entendimento do que está sendo questionado. Os formulários já estão prontos para aplicação (em português e japonês)

Todas as seis PMEs selecionadas para responder a pesquisa partilham do mesmo setor de atuação: setor metal mecânico e podem ser observadas algumas informações gerais delas na Tabela 4. Sendo que elas atendem aos requisitos de número de funcionários mínimo e máximo para serem consideradas pequenas ou médias empresas no país no qual atuam. Apesar das características básicas de todas elas serem as mesmas, há grandes diferenças na forma com o qual cada empresa é conduzida, sendo assim, possivelmente haja diferenças de aderência dos facilitadores.

Tabela 4 - Empresas selecionadas e ramo de atuação.

EMPRESAS	ÁREA DE ATUAÇÃO DAS EMPRESAS
E1 - Japão	Fabricante de corrente de metal
E2 - Japão	Fabricante de equipamentos de mecatrônica
E3 - Japão	Fabricante de materiais de cobre e metal
E4 - Brasil	Fabricante de implementos agrícolas e equipamentos rodoviários
E5 - Brasil	Fabricante de equipamentos e suprimentos para escritório, consolidada nos segmentos de automação e manufatura
E6 - Brasil	Fabricante de equipamentos industriais, projetos para fabricas de ração, manutenção industrial, engenharia de processos

Fonte: Os autores.

O método AHP foi aplicado com três especialistas de cada país, sendo que dentro do mesmo país eles residem em regiões distintas, com o intuito de avaliar o local como um todo e não baseado apenas em uma pequena região. Cada um dos respondentes avaliaram de acordo com seus conhecimentos prévios na área quais as características das PMEs que são mais importantes ou determinantes no crescimento delas.

Nas respostas dos especialistas japoneses, a característica mais determinante dentro de uma pequena ou média empresa é a alta incidência de inovação (peso 0,413), seguida pela flexibilidade da empresa em se adaptar às mudanças impostas pelo mercado (peso 0,232). Também pode ser observado que essas duas características tem peso bem superior às outras colocações. Para os respondentes brasileiro a ordem das duas primeiras características se mantém, sendo em primeiro lugar a alta incidência de inovação (peso 0,251) e seguido pela flexibilidade da empresa (peso 0,229). As respostas de brasileiros apresentaram pouca disparidade entre as colocações no *ranking*.

Os pesos atribuídos pelos especialistas podem ser observado na Tabela 5, no qual estão evidenciados separadamente os pesos atribuídos por especialistas japoneses e por especialistas brasileiros.

Tabela 5 - Resultado AHP

CRITÉRIOS	JAPÃO		BRASIL	
	MÉDIA	RANKING	MÉDIA	RANKING
C1 - Flexibilidade	0,232	**2º**	0,229	**2º**
C2 - Dificuldade no NPD	0,067	**5º**	0,179	**3º**
C3 - Inovação	0,413	**1º**	0,251	**1º**
C4 - Recursos Limitados	0,087	**4º**	0,165	**5º**
C5 - Alta Autoridade	0,200	**3º**	0,176	**4º**

Fonte: Os autores

O método TOPSIS 2-*Tuple* (fase 2) está sendo aplicado e os resultados estarão descritos na versão estendida desse artigo.

5 Conclusão

Esse trabalho apresenta 18 facilitadores do *lean* e do *green*, apresentados como as alternativas para os métodos multicritérios, sendo todas elas encontradas a partir de

revisões de literatura. A partir da aplicabilidade delas na prática é possível compreender qual o grau de maturidade das PMEs quanto às metodologias *lean* e *green*.

Os resultados da fase 1 foram satisfatórios, uma vez que foram abordados profissionais de diferentes áreas de atuação para responder ao método AHP e obtive-se resultados bem positivos com essa heterogeneidade de respondentes. As características tidas como principais, elencadas entre as duas primeiras posições, foram as mesmas em ambos os países, porém as últimas sofreram alterações de colocações.

Pode-se observar ainda que os especialistas japoneses classificam as três primeiras colocadas: Inovação, Flexibilidade e Alta autoridade, com bastante disparidade de pontuação frente às últimas colocadas. Já os especialistas brasileiros apresentam os resultados muito mais próximos uns dos outros, atribuindo importâncias semelhantes.

A fase 2 permite avaliar dentro das empresas do setor metal mecânico o quanto estão aplicados os facilitadores do *lean* e do *green*. Bem como avaliar se há práticas desenvolvidas dentro das empresas que sejam consideradas importantes e replicáveis para outras empresas. Cada uma das empresas avaliadas apresenta uma forma de gerenciamento, sendo assim, bem heterogêneas entre si.

Ainda, com esse estudo, a alta gerência pode perceber onde encontram-se os pontos fracos do NPD dentro da empresa. E, a partir disso, focar em ações que visem melhorar os pontos elencados, trazendo maior aderência aos facilitadores e metodologias do *lean* e do *green.*

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Multi-objective optimization of a rotary dryer in a semi-dynamic state using evolutionary algorithms

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Abstract. The multi-objective optimization of a direct current rotary dryer that works with pozzolan in a semi-dynamic condition is described in this article. Four objective functions are minimized using the NSGA-II algorithm, these objective functions are: (1) the pozzolan humidity at the exit of the rotary dryer, (2) the heat given off by the rotary dryer to the environment, (3) the operating costs of the production process and (4) the number of new starts of the rotary dryer. The operating parameters for the 24-hour simulation were obtained. Simulation results show that it is not recommended to interrupt the dryer operation due to the high operating costs that this generates.

Keywords: rotary dryer · multi-objective optimization · pozzolan · evolutionary computing.

Resumen La optimización multiobjetivo de un secador rotatorio de corriente directa que trabaja con puzolana en condición semi-dinámica se describe en este artículo. Cuatro funciones objetivos son minimizadas utilizando el algoritmo NSGA-II, estas funciones objetivos son: (1) la humedad de la puzolana a la salida del secador rotatorio, (2) el calor cedido por parte del secador rotatorio hacia el medio ambiente, (3) los costos operativos del proceso de producción y (4) el número de nuevos encendidos del secador rotatorio. Se obtuvo los parámetros operativos para las 24 horas de simulación y además se observó que una vez encendido el secador rotatorio no es recomendable interrumpir su operación debido a los altos costos operativos que esto genera.

Palabras claves: secador rotatorio· optimización multiobjetivo· puzolana· computación evolutiva.

1 Introducción

Este trabajo apunta a mejorar los parámetros operativos del secador rotatorio de la Industria Nacional del Cemento del Paraguay (INC), en condiciones semi-dinámicas, a fin de reducir los costos operativos, el contenido de humedad en la puzolana a la salida del secador rotatorio, la emisión de calor al medio ambiente por parte del secador y el número de paradas del secador rotatorio.

En un ambiente tradicional mono-objetivo, es decir, donde se combinan los objetivos a ser optimizados en una sola función objetivo, el problema de optimización puede reducirse a la búsqueda de un máximo o mínimo que sería la solución del problema. Por el contrario, cuando se necesitan considerar simultáneamente los diversos objetivos y estos objetivos se contraponen unos con otros por existir relaciones de compromiso, no siempre existe una única solución al problema, sino un conjunto de soluciones [1]; esto se conoce como Problema de Optimización Multiobjetivo (*Multi-Objective Optimization Problem - MOP*).

Douglas et al. [2], realizaron una simulación transitoria de un secador rotatorio que procesa cristales de azúcar y obtuvieron respuestas dinámicas de los perfiles de humedad y temperatura para el proceso teniendo como entrada una función escalón para ambos casos.

El diseño y operación de los secadores convectivos en el cual se incluye a los secadores rotatorios, fue estudiado por Kiranoudis et al. [3], evaluando los parámetros operacionales de cada secador en términos del costo anual total.

Lobato et al. [4], utilizaron técnicas de optimización multiobjetivo del tipo *Firefly Algorithm* (FA) para la estimación de parámetros de la cinética de secado y calculan los coeficientes de pérdida de calor para una planta piloto de un secador rotatorio que procesa superfosfatos.

Álvarez L. et al. [5], analizaron el diseño óptimo de los parámetros físicos característicos de un secador rotatorio que procesa puzolana, mejorando la reducción en el contenido de humedad de la puzolana en un porcentaje de hasta 6%. De este modo, se logró aumentar la capacidad de producción de una planta industrial cementera.

Miranda [6], mejoró la capacidad de producción de una planta industrial cementera boliviana, mediante el uso del software *Design Expert*, minimizando la pérdida de calor con el ambiente del secador rotatorio de puzolana y minimizando el contenido de humedad de la puzolana.

La optimización multiobjetivo de un secador rotatorio en contracorriente para el secado de fertilizantes del tipo superfosfatos simples, fue propuesto por Silveira et al. [7], donde utilizando algoritmos de Evolución Diferencial (ED) y un modelo robusto, obtuvieron las mejores condiciones de operación del secador, minimizando el calor perdido por las paredes del secador rotatorio y minimizando el contenido de humedad al final de la longitud del secador, considerando la determinación de la temperatura inicial del aire en la entrada del secador, la velocidad del aire y el flujo másico de los sólidos.

Shene et al. [8] modelaron y simularon un secador rotatorio de corriente directa que procesa pescado y soja, donde mediante un modelo distribuido obtuvieron el perfil de temperatura del aire de secado y el perfil de temperatura de los sólidos tratados, comparándolos también con los datos experimentales obtenidos en una planta piloto.

En contrapartida a los trabajos anteriores arriba descriptos, este trabajo considera por primera vez la minimización simultánea de cuatro funciones objetivo en el secado de puzolana con un secador rotatorio y en condiciones semi-dinámicas, en un contexto puramente multiobjetivo. En efecto, utilizando un MOEA (*Multi-objective Optimization Evolutionary Algorithm*) se optimiza: (1) la humedad a la salida del secador rotatorio, (2) el calor cedido al ambiente por el secador, (3) los costos operativos en el proceso de secado de la puzolana y (4) los costos de mantenimiento del secador.

En la siguiente sección se plantea formalmente el MOP y el modelado matemático en corriente directa; en la Sección 3 se resume la metodología general y el algoritmo utilizado en la resolución del MOP. En la Sección 4 se resumen los resultados experimentales obtenidos. Por último se establecen las conclusiones y los trabajos futuros en la Sección 5.

2 Problema de optimización multiobjetivo

Formalmente, una optimización multiobjetivo (*Multi-Objective Optimization*), se refiere a la optimización (minimización o maximización) simultánea de dos o más funciones objetivos, donde los objetivos podrían entrar en conflicto unos con otros [9]. El problema de optimización se establece como sigue:

$$Optimizar \quad F(x) = [f_1(x), f_2(x), ..., f_n(x)] \tag{1}$$

Sujeto a:

$$g_i(x) \leq 0 \qquad i = 1, 2, ..., n_i \tag{2}$$

$$h_i(x) = 0 \qquad i = 1, 2, ..., n_e \tag{3}$$

$$x_l \leq x \leq x_u \tag{4}$$

donde n representa al número de funciones objetivos a ser optimizados simultáneamente, x es un vector de m variables de decisión (continuos o discretos) con valores límites; *lower* (x_l) y *upper* (x_u), mientras que n_i y n_e son el número de restricciones en forma de inecuaciones e igualdades, respectivamente.

El espacio factible, Ω es un conjunto de vectores de x que satisfacen todas las restricciones de (2) a (4). La imagen de los vectores de $x \in \Omega$ crean el espacio objetivo simbolizado con la letra Λ [10].

Dominancia Pareto:

Sean $\mathbf{A}, \mathbf{B} \in \Omega$, se dice que $\mathbf{A}$ domina a $\mathbf{B}$ si $\mathbf{A}$ es igual o mejor a $\mathbf{B}$ en todos los objetivos y estrictamente mejor en al menos un objetivo. En este caso, se dice que existe dominancia de $\mathbf{A}$ respecto a $\mathbf{B}$ lo que se denota como $\mathbf{A} \succ \mathbf{B}$ ($\mathbf{A}$ es mejor que $\mathbf{B}$) [11].

Un vector $x^* \in \Omega$ en la región factible es Pareto óptimo [9, 12], si no existe otro vector factible $x \in \Omega$ que pudiera mejorar alguna función objetivo sin causar el detrimento simultáneo en al menos otra función objetivo. Las soluciones Pareto óptimas también se denominan soluciones no dominadas. El conjunto de soluciones no dominadas se conoce como conjunto Pareto (P) y su imagen en el espacio objetivo Λ se denomina Frente Pareto (FP).

2.1 Modelado matemático del secado en corriente directa en estado semi-dinámico

Las siguientes consideraciones se establecen para presentar el modelo semi-dinámico del secador rotatorio en corriente directa [3, 12]:

- se considera que el secador y el quemador operan en estado semi-dinámico, teniendo en cuenta la variación de la temperatura ambiente a lo largo de un día y la variación de la demanda de puzolana;
- ninguna propiedad varía con la posición en el volumen de control (modelo concentrado);
- se considera a la entalpía prácticamente independiente de la presión;
- se considera que la reacción de combustión del biofuel es completa en el quemador;
- para el cálculo del calor cedido por el secador a los alrededores sólo se considera el término convectivo, despreciándose los aportes de conducción de calor y de radiación.

El esquema del proceso a estudiar se muestra en la Figura 1, en donde se puede visualizar que la unidad del proceso de secado consta de dos unidades, un quemador y un secador rotatorio. En el quemador ingresa biofuel conjuntamente con aire húmedo en corriente directa, se produce la combustión, que se considera completa y los gases de combustión que salen del quemador ingresan al secador rotatorio de corriente directa acompañado con la puzolana húmeda. En esta unidad se produce la transferencia de calor y masa así, en el secado parte de la humedad de la puzolana se evapora y pasa a la fase vapor que finalmente forma parte de los gases de escape. Entonces, del secador rotatorio salen: la puzolana seca, que es el producto principal en este proceso y los gases de escape, que se devuelven a la atmósfera.

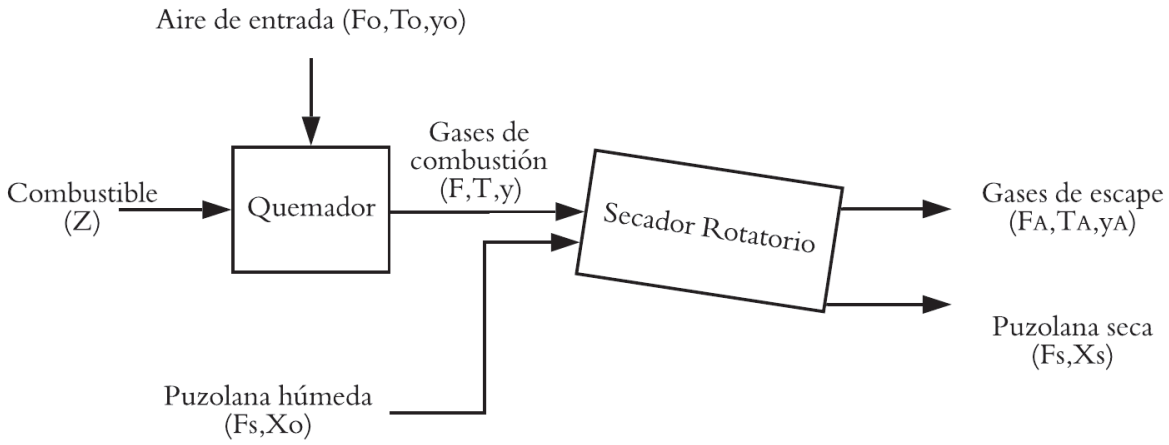

Fig. 1. Diagrama del secador y el quemador de la unidad del proceso de secado.

2.2 Objetivos de la optimización multiobjetivo en corriente directa

Humedad de la puzolana a la salida del secador (f_1): La humedad de la puzolana a la salida del secador debe ser mínima para que la operación de molienda (operación que sigue al secado en una planta cementera) no se vea dificultada.

El balance de materia en el quemador se detalla a continuación, asumiendo que el combustible usado es un biofuel, hidrocarburo con un calor de combustión igual a ΔH_f [kJ/kg] y una fracción de hidrógeno C_H [kg/kg] y que la reacción química de combustión es [12]:

$$C + O_2 \rightarrow CO_2 \tag{5}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{6}$$

Se producen entonces, $9C_H$ [Kg] de vapor de agua por [Kg] de combustible [12], esto es:

$$R_w = 9C_H Z \tag{7}$$

donde:

R_w: Velocidad de producción de agua, $[kg/s]$.

El balance total de materia y de agua sobre el quemador se obtiene aplicando las siguientes relaciones [3, 12]:

$$F(1 + y) = F_o(1 + y_o) + Z \tag{8}$$

$$Fy = F_o y_o + R_w \tag{9}$$

donde:

F: Caudal másico de los gases de combustión salida del quemador, $[kg/s]$.
F_o: Caudal másico del aire de entrada al quemador, $[kg/s]$.
y: Humedad de los gases de combustión en la entrada del secador, $[kg/kg\ AS]$.
y_o: Humedad absoluta del aire en la entrada del quemador, $[kg/kg\ AS]$.
Z: Caudal másico del combustible, $[kg/s]$.

Se asume que los gases de combustión tienen las mismas propiedades físicas que el aire, por lo tanto el balance de energía en el quemador queda como [12]:

$$F(1+y)Cp_a(T - T_o) = Z\Delta Hf \tag{10}$$

donde:

Cp_a: Calor específico de los gases de combustión, $[kJ/kg°\mathrm{C}]$.
ΔH_f: Calor de combustión, $[kJ/kg]$.
T: Temperatura de entrada de los gases de combustión al secador, $[°C]$.
T_o: Temperatura ambiente, $[°C]$.

Aplicando un balance de materia total en el secador rotatorio, se obtiene la siguiente relación matemática para la humedad de salida de la puzolana [3, 12]:

$$f_1 = X_o - \frac{F}{F_s}(y_a - y) \tag{11}$$

donde:

f_1: Humedad de la puzolana a la salida del secador rotatorio, $[kg/kg]$.
F_s: Caudal másico de puzolana sólida en el secador rotatorio, $[kg/s]$.
X_o: Humedad de la puzolana en la entrada del secador, $[kg/kg]$.
y_a: Humedad de los gases de combustión en la salida del secador, $[kg/kg\ AS]$.

Calor cedido por el secador rotatorio al ambiente (f_2): El calor cedido por el secador rotatorio al ambiente debe ser minimizado debido a tres motivos: (1) optimizar el calor cedido por el combustible para el secado de la puzolana, (2) disminuir el impacto térmico al ambiente, (3) mejorar los parámetros operativos, considerando que estas son variables independientes del problema planteado.

El calor que pierde el secador rotatorio es debido a mecanismos convectivos principalmente, y está dado por la siguiente relación matemática [2]:

$$f_2 = KF^m \pi DL(T - T_o)b_i \tag{12}$$

donde:

D: Diámetro del secador, [m].
f_2: Calor cedido por el secador rotatorio hacia el ambiente, $[w]$.
K: Constante del proceso obtenido experimentalmente, $[W/m^{2\circ}\ C]$.
L: Longitud del secador, [m].
m: Constante adimensional del proceso de secado.
b_i: Número binario que puede valer 0 o 1, según el secador esté apagado o prendido respectivamente en el intervalo i.

Costos operativos (f_3): Los costos operativos considerados en este trabajo incluyen al costo de la energía eléctrica consumida por el secador rotatorio y el costo del combustible, en este caso biofuel usado en el quemador, por lo que no se consideran como variables a otros costos como los salarios de los funcionarios que operan en el sector de secado. Un factor importante es el costo de la energía eléctrica en la estructura tarifaria de la misma [1]. Existe diferencia de precios, denominada tarifa diferenciada, que para el presente trabajo se considera como sigue:

- tarifa barata (C_{ef}): de 0 a 17 hs, y de 22 a 24 hs., denominado horario fuera de punta de carga;
- tarifa cara (C_{ep}): de 17 a 22 hs., llamado horario de punta de carga.

El costo operativo está determinado por la siguiente ecuación [1, 3, 12]:

$$f_3 = qN_iD(M+W)C_{ei}t_{op}bi + ZC_{zi}t_{op}bi \tag{13}$$

donde:
C_{ei}: Costo de la energía eléctrica en el i-ésimo intervalo, $[US\$/KWh]$.
C_{zi}: Costo unitario del combustible,$[US\$/KWh]$.
f_3: Costo operativo total, $[US\$]$.
M: Masa de puzolana en el secador rotatorio, $[kg]$.
N_i: Velocidad de rotación en el i-ésimo intervalo, [rpm].
q: Coeficiente adimensional para la función de costos operativos.
t_{op}: Tiempo operativo, $[s]$.
W: Masa del secador rotatorio, $[kg]$.

Costo de mantenimiento del secador rotatorio (f_4): El costo de mantenimiento es igual o inclusive más importante que los costos operativos [1]. Se introduce el concepto de número de encendidos del secador rotatorio como una forma de medir el costo de mantenimiento. Es decir, se mide de forma indirecta el costo de mantenimiento del secador por medio del número de veces que ha sido encendido. A mayor número de encendidos, mayor costo de mantenimiento. Un encendido se considera como tal solo en el caso que el secador rotatorio haya estado apagada en el intervalo de tiempo anterior [1].

Si el secador rotatorio ya estaba encendido en el intervalo anterior y continúa estándolo o se apaga en el intervalo siguiente, no constituye un encendido. Para determinar el número total de encendidos f_4 simplemente se cuenta el número de encendidos en cada intervalo y a esto se suma la mitad del número de encendidos entre el primer y el último intervalo; esto último, de manera a considerar los encendidos que hubieran entre el día anterior y el actual, suponiendo cierta periodicidad en las programaciones. Lo explicado anteriormente puede ser expresado como:

$$f_4 = \sum_{i=1}^{24} \left\| max\left\{0; (b_i - b_{i-1})\right\}\right\|_1 + \frac{\left\| max\left\{0; (b_1 - b_{24})\right\}\right\|_1}{2} \tag{14}$$

2.3 Planteamiento matemático del problema formulado

Minimizar $\boldsymbol{y=f(x)}=[f_1(x),f_2(x),f_3(x),f_4(x)]^T$
donde:

f_1 : humedad de la puzolana a la salida del secador rotatorio; ver ecuación (11).
f_2 : calor cedido por el secador rotatorio al ambiente; ver ecuación (12).
f_3 : costos operativos; ver ecuación (13).
f_4 : número de encendidos del secador rotatorio, ver ecuación (14).
$\mathbf{y} \in R^4$;

$\mathbf{x}= [x_1; x_2; x_3; x_4; x_5] \in R^5$, es el vector de las variables independientes, también denominado variables manipulables, donde:

$x_1 = N \in R$, representa la velocidad de rotación en rpm;
$x_2 = T \in R$, representa la tempertaura de los gases de combustión en la entrada del secador rotatorio en °C;
$x_3 = Z \in R$, representa el caudal másico de combustible en la entrada del quemador, en kg/s;
$x_4 = F_o \in R$, representa el caudal másico de aire en la entrada del quemador en kg/s.
$x_5 = b_i \in \{0, 1\}$ es un número binario representa al estado apagado o encendido del secador en el intervalo i.

sujeto a: $x_l \leq x \leq x_u$
donde:

$x_l = [1; 600; 0.1; 10; 0]$
$x_u = [10; 900; 1; 1000; 1]$

3 Metodología

El modelo en estado semi-dinámico pretende determinar el conjunto de soluciones Pareto óptimos $\mathbf{P}$, minimizando la función objetivo $y = f(x)$ y considerando la variación de la temperatura ambiente y la variación de la demanda de puzolana, en cuyo caso se requiere volver a correr el algoritmo de optimización para cada hora del día.

Variación de la temperatura ambiente En la Figura 2 se presenta la variación de la temperatura ambiente considerada como ejemplo, a lo largo de un periodo de 24 horas. Ésta puede obtenerse a través de los datos del pronóstico del tiempo provistos por la Dirección de Meteorología e Hidrología[3] (DMH).

[3] http://www.meteorologia.gov.py/, consultado el 03/12/2019 a las 15:39 hs

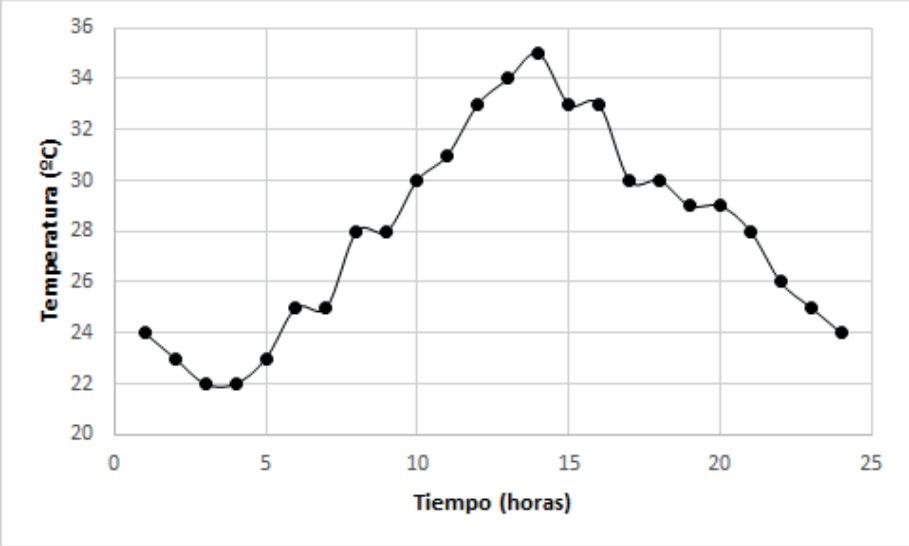

Fig. 2. Variación de la temperatura ambiente en un día (Fuente: Elaboración propia).

Variación de la demanda de puzolana Empíricamente, en la INC se realiza la distribución de la demanda en función de la temperatura ambiente, es decir; los horarios en donde es mayor la temperatura ambiente conviene aumentar la carga del secador de puzolana, y a lo largo de las 24 horas satisfacer la demanda total diaria establecida por el Departamento de Producción.

La variación de la demanda sigue una distribución estocástica, es decir, expresadas según funciones de probabilidad [14]. Matemáticamente, la demanda dentro de las 24 horas se puede expresar como:

$$\sum_{k=1}^{24} Fs_k = Fs_T \tag{15}$$

donde:

k: intervalo de optimización de 1 hora.
Fs_k: Demanda de puzolana en el intervalo $k - ésimo$, en Kg/h.
Fs_T: Demanda total de puzolana seca, en Kg/h.

Si cada demanda en un $k - ésimo$ intervalo de tiempo es función lineal a la temperatura ambiente en dicho instante, entonces:

$$\begin{aligned} Fs_1 &= \beta To_1 \\ Fs_2 &= \beta To_2 \\ &\dots \\ Fs_{24} &= \beta To_{24} \end{aligned} \tag{16}$$

De las ecuaciones (15) y (16), se obtiene el coeficiente de proporcionalidad β, como sigue:

$$\beta = \frac{Fs_T}{\sum_{k=1}^{24} To_k} \tag{17}$$

donde:

β: Coeficiente de proporcionalidad.

To_k: Temperatura ambiente en el $k-ésimo$ intervalo de tiempo, en $°C$.

Para satisfacer por ejemplo, una demanda diaria de 840 toneladas de puzolana y siguiendo la distribución de la temperatura ambiente dada en la Figura 2, el valor puntual de $\beta \approx$1254. En este caso la distribución de la demanda se muestra en la Figura 3.

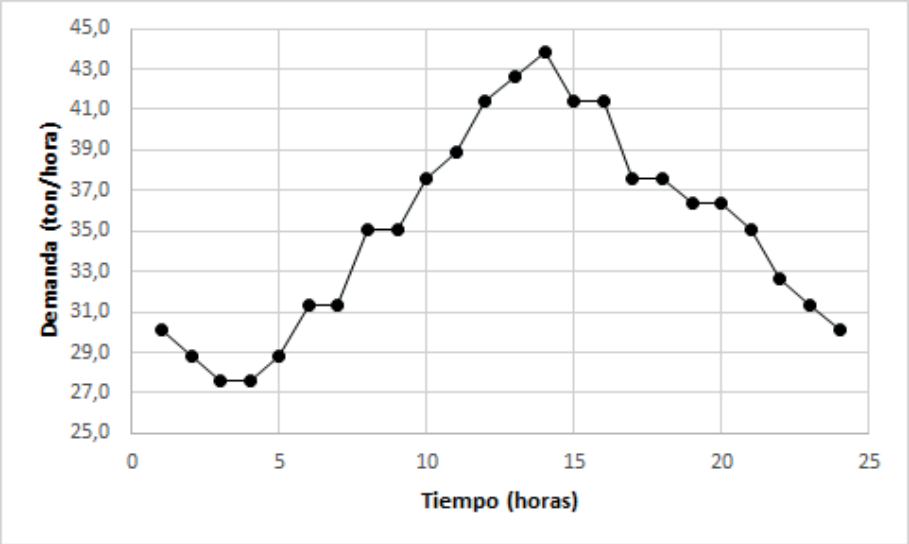

Fig. 3. Variación de la demanda en un día (Fuente: Elaboración propia).

Se tendrán en total 24 simulaciones, 1 simulación para cada hora del día.

El algoritmo utilizado para obtener los datos experimentales que se muestran a continuación es el NSGA-II [13], con un número de generaciones igual a 400, y un tamaño de población igual a 200.

Se utilizó el software Matlab $R2020a$, y un ordenador con un procesador AMD E1-200 APU con Radeon (TM) DD Graphics, 1000 MHz con 2 procesadores lógicos y memoria de 4 GByte.

4 Resultados

En la Tabla 1 se presentan los datos utilizados en las simulaciones presentadas para un proceso semi-dinámico de un día (24 horas).

Tabla 1. Datos del proceso de secado en estado semi-dinámico

Parámetro	Valor
D (m)	2
L (m)	15
U ($W/m^2\ ^\circ C$)	28.36
$T_o(^\circ C)$	según Fig. 2
q	1
Ce (US$/W)	$7*10^{-5}$
Cz (US$/W)	$5*10^{-5}$
M (kg)	1000
W (kg)	10000
C_H (kg/kg)	0.106
ΔH_f (kJ/kg)	$15*10^6$
Cp_a(kJ/kg$^\circ C$)	1180
y_o (kg/kgAS)	0.01
X_o (kg/kg)	1
ΔH_V (kJ/kg)	$2.5*10^6$
F_s (kg/s)	según Fig. 3

En la Figura 4 se muestran los resultados obtenidos para los periodos de simulación de t=1h a t=24h para la optimización multiobjetivo realizada, utilizando coordenadas paralelas. Para cada corrida se obtienen 224 conjuntos Pareto y cada conjunto Pareto tiene varias familias (subconjuntos) de soluciones. En las poli-líneas azules de la Figura 4 se minimizan las funciones objetivos de humedad a la salida del secador rotatorio (f_1) y de costos de mantenimiento (f_4). Por otro lado, en la Figura 4 se puede ver otra familia de soluciones representado por las poli-líneas de color naranja, en donde se minimizan preferentemente las funciones objetivo de emisión de calor al ambiente f_2 y los costos operativos f_3.

Un operador de la INC al ingresar a su turno de trabajo debe ingresar al ordenador (donde se tiene instalado el algoritmo de optimización multiobjetivo) las proyecciones por hora de la temperatura ambiente T_o y de la demanda F_s para lo que dure su jornada laboral. El ordenador le proporcionará como información de salida: la velocidad angular a la cual debe mantener el secador rotatorio x_1, la temperatura a la cual deben ingresar los gases de combustión al secador rotatorio x_2, el caudal másico del fuel-oil que debe ingresar al quemador x_3, el flujo másico del aire de entrada x_4 y si debe o no apagar el secador rotatorio x_5. Si existe alguna perturbación en la temperatura ambiente o en la demanda de la puzolana durante la jornada laboral, el operador deberá volver a ingresar estos nuevos datos al ordenador y ajustar las variables de decisión (x) del proceso.

Cabe destacar que los mejores resultados realizan 0 nuevos encendidos una vez que el secador entra en marcha, minimizando los altos costos de mantenimiento.

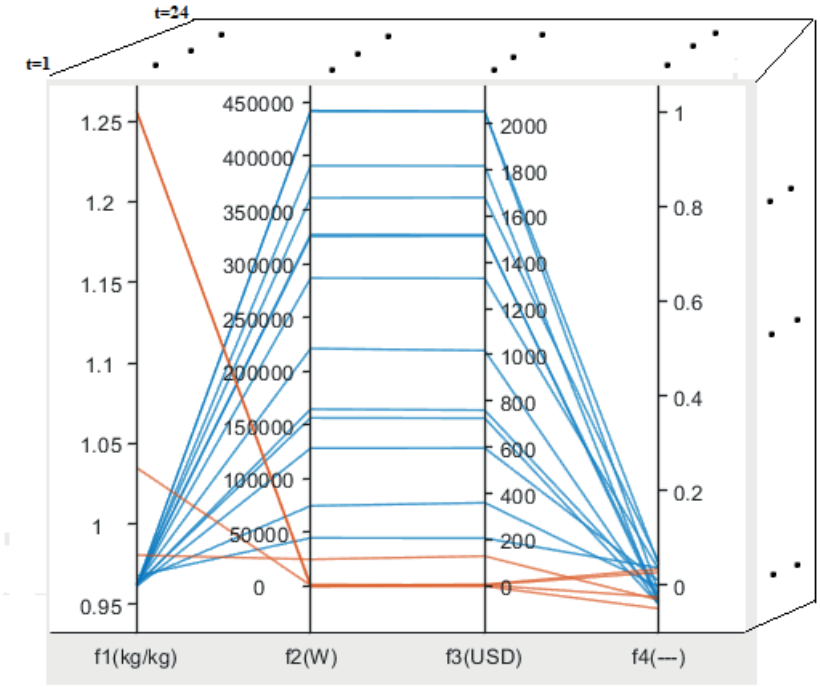

Fig. 4. Esquema de los resultados obtenidos en la optimización multiobjetivo en coordenadas paralelas.

5 Conclusión y trabajos futuros

Se obtuvo los parámetros operativos del secador rotatorio en condiciones semi-dinámicas para las 24 horas de simulación. Una vez encendido el secador rotatorio, se comprobó que no es recomendable apagarlo pues aumenta excesivamente los costos de mantenimiento.

Para trabajos futuros se recomienda analizar el modelo dinámico real, en donde en cualquier momento del día puede ocurrir una perturbación en la demanda o en la temperatura ambiente.

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Modelado mecanístico de procesos de molienda de maíz: Calibración de parámetros para el modelado por elementos discretos (DEM)

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Abstract. En este trabajo se determinaron experimentalmente las propiedades más relevantes de granos de maíz (coeficiente de restitución, coeficiente de fricción, módulo de Young, densidad, ángulo de reposo) y se calibró el coeficiente de fricción intergranular para poder simular la rotura del maíz en el software Rocky DEM (ESSS). Además, se realizó un estudio de sensibilidad para determinar los parámetros del modelo de rotura, cuyos resultados representan adecuadamente al caso de estudio. La calibración se llevó a cabo replicando en Rocky DEM ensayos de medición del ángulo de reposo y se obtuvo un coeficiente de fricción intergranular de 0.31.

Keywords: DEM, calibración, molienda.

1 Introducción

La molienda de material particulado es una operación que reviste gran importancia a nivel industrial. Se estima que el 60% de los productos manufacturados se presentan en forma de polvo o requieren algún tipo de procesamiento de partículas [1]. A pesar de esto, la complejidad de su modelado y la falta de ecuaciones que describan adecuadamente su comportamiento, los torna ineficientes, dificultando su escalado y control.

El resultado de la molienda está determinado por las propiedades del material, el equipo utilizado y las condiciones operativas. Los enfoques tradicionales, basados en balances de energía, no tienen la capacidad de representar los fenómenos que ocurren en los sistemas de partículas. Por este motivo, el modelado por elementos discretos (DEM) ha cobrado gran importancia en la resolución de este tipo de problemáticas.

Las propiedades físicas del material son esenciales para estudiar su comportamiento y para una adecuada simulación en software DEM. Estas propiedades pueden medirse a escala de partícula (micro propiedades) o a granel (macro propiedades). Entre las micro propiedades se encuentran tamaño y forma de partícula, densidad de partícula, módulo de Young y coeficiente de Poisson del material, coeficiente de restitución (partícula-partícula

y partícula-entorno) y coeficiente de fricción (partícula-partícula y partícula-entorno); y entre las macro propiedades, la densidad a granel, el ángulo de fricción interna, el ángulo de dilatación y el ángulo de reposo. Es importante destacar que las macro propiedades no se pueden especificar como parámetros de entrada en un modelo DEM, sino que deben ser correctamente predichas mediante simulaciones de arreglos de partículas que presenten el mismo comportamiento que el material físico. Usualmente, las propiedades necesarias como parámetros de entrada de los modelos DEM se obtienen mediante ensayos experimentales o, en el caso que no sea posible medirlas directamente, deben calibrarse. Para ello, se realizan experimentos de laboratorio que permiten medir una propiedad específica del material a granel (i.e., ángulo de reposo, densidad a granel). El experimento luego se replica numéricamente siguiendo la configuración y los procedimientos de laboratorio lo más cercano a la realidad posible (experimento virtual). Los valores de los parámetros de entrada de DEM se cambian iterativamente hasta que el valor simulado de la propiedad a granel coincida con el resultado medido.

En este trabajo, se determinaron las propiedades físicas del maíz, principal componente en la industria de alimentos balanceados, y se simuló en el software Rocky DEM (ESSS).

1.1 Método de elementos discretos (DEM)

El método de elementos discretos consiste en modelar un material granulado como partículas individuales que interactúan entre sí y con su entorno. Utiliza sofisticadas técnicas numéricas para resolver las leyes de movimiento de Newton y se basa en la mecánica de contacto para predecir la fragmentación y trayectoria de las partículas tras una colisión. La dirección del movimiento y la velocidad se calculan en intervalos discretos, describiendo el proceso con elevado nivel de detalle [2][3]. En este trabajo, las simulaciones DEM se realizaron en el software Rocky DEM (ESSS), el cual posee capacidades únicas, tales como su modelado del proceso de rotura y la posibilidad de combinar diferentes formas y tamaños para crear conjuntos de partículas únicos y cercanos a la realidad, en vez de los típicos grupos de esferas que se encuentran en otros programas DEM [4].

Tal como se mencionó, para definir el modelo de contacto, la simulación en Rocky requiere un conjunto de parámetros de colisión y propiedades del material que deben determinarse cuidadosamente para obtener resultados acertados.

1.2 Módulo de Young

El módulo de Young es una propiedad que describe la rigidez de un material. Refleja la relación entre el esfuerzo y la deformación que experimenta el material al ser sometido a una carga externa, en una dirección dada [5]. Su determinación se realiza con partículas individuales, aplicando ecuaciones de contacto y teniendo en cuenta las características del equipo de compresión, que deben ajustarse a la forma y tipo de material particulado [6].

1.3 Representación de las partículas en DEM

Para llevar a cabo simulaciones cuyos resultados sean representativos del comportamiento real, las propiedades de las partículas virtuales deben aproximarse de la manera más cercana posible a aquellas propias del material. Una de estas propiedades es la forma. Debido a la irregularidad de los materiales granulados, se suele recurrir a formas simplificadas para representarlos. El modelado más sencillo corresponde al uso de esferas, cuyo tiempo de cómputo suele ser reducido pero los resultados que se obtienen son de baja fiabilidad.

1.4 Coeficiente de fricción partícula/entorno

Cuando se tiene dos superficies en contacto, y una de ellas se pone en movimiento o comienza a deslizarse, se genera una fuerza que se opone a este desplazamiento. El coeficiente de fricción es la propiedad que relaciona la fuerza de fricción y la fuerza normal, y es uno de los parámetros básicos requeridos en las simulaciones DEM.

1.5 Ángulo de reposo estático

El ángulo de reposo se define como el ángulo máximo en el cual una pila de material particulado se encuentra inmóvil sobre una superficie plana. El material empieza a fluir en ángulos mayores, mientras que en ángulos menores se mantiene estable. Suele variar entre 25º para partículas cuasi esféricas y 45º para partículas muy irregulares [7].

1.6 Coeficiente de restitución partícula/entorno e intergranular

El coeficiente de restitución de una partícula se define como la relación absoluta entre las velocidades antes y después de una colisión. Representa el grado de conservación de la energía cinética tras la colisión, ya sea entre la partícula y el entorno, o entre partículas. Se trata de uno de los parámetros fundamentales en el modelado DEM, que ayuda a predecir el comportamiento de las partículas después de una colisión dentro un sistema.

1.7 Coeficiente de fricción intergranular

El coeficiente de fricción intergranular ofrece una medida de la resistencia que presentan las partículas al movimiento, al ponerse en contacto unas con otras. Este parámetro es complejo de ser determinado experimentalmente, por lo que suele ser calibrado mediante replicación de ensayos de otros experimentos, ajustando el valor en el software DEM hasta llegar a resultados similares a los experimentales.

1.8 Parámetros de rotura

Los parámetros que afectan la rotura son inherentes a cada modelo. Para ajustarlos, se deben implementar experimentos de rotura de las partículas individuales y realizar simulaciones variando los parámetros hasta obtener resultados adecuados. Rocky DEM cuenta con el modelo de rotura desarrollado por Tavares et al. [10], el cual se describe a continuación:
a) Acumulación de daño luego de un impacto sin rotura. Las energías específicas de fractura de partícula en sucesivos eventos de carga pueden cuantificarse con la expresión:

$$E_n = E_{n-1}(1 - D_n^*) \quad (1)$$

siendo D_n^* el daño sostenido en el n-ésimo ciclo de carga, igual a:

$$D_n^* = \left[\frac{2\gamma}{(2\gamma - 5D_n^* + 5)} \frac{E_{k,n}}{E_{n-1}}\right]^{\frac{2\gamma}{5}} \quad (2)$$

donde γ es el coeficiente de acumulación de daño, cuya determinación es compleja.
b) Fragmentación de la partícula. La distribución de tamaño generada por los impactos de energía específica $E_{k,n}$ sobre partículas de una misma clase se calcula estimando la fracción del material que pasa a 1/10 del tamaño original de partícula (t_{10}):

$$t_{10} = A\left[1 - exp\left(-\frac{b' E_{k,n}}{E}\right)\right] \quad (3)$$

donde A y b' son parámetros del modelo y E es la energía específica de fractura de las partículas que se rompen con una energía de impacto $E_{k,n}$.
Al volverse más finas las partículas, se vuelven también más duras y se incrementa su energía específica de fractura. La siguiente expresión se utiliza para describir esta variación:

$$E_{50} = E_\infty \left[1 + \left(\frac{d_0}{L}\right)^{\varphi}\right] \quad (4)$$

donde d_0, E_∞ y φ son parámetros del modelo que se ajustan con datos experimentales y L es el tamaño representativo de las partículas, todos ellos varían mucho con el material.
c) Distribución de la energía específica de fractura. La ecuación (5) define la distribución de la energía específica de fractura como:

$$P_0(E) = \frac{1}{2}\left[1 + erf\left(\frac{\ln E^* - ln E_{50}}{\sqrt{2\sigma^2}}\right)\right] \quad (5)$$

donde σ^2 es la varianza de la distribución normal logarítmica de energías de fractura, E_{50} es la energía específica media de fractura y E^* es la energía específica relativa de fractura:

$$E^* = \frac{E_{max} E}{E_{max} - E} \quad (6)$$

donde E_{max} es la energía específica de fractura por sobre la cual todas las partículas se rompen en un solo impacto.

2 Metodología

2.1 Medición de la densidad y el módulo de Young

La densidad de los granos fue determinada mediante picnometría, utilizando agua como líquido de referencia. Para determinar el módulo de Young se realizaron ensayos de

compresión empleando un texturómetro (TA Instruments). El mismo consiste en una celda que aplica tensión de manera controlada a muestras sólidas, midiendo su perfil completo de deformación. Se utilizó un cabezal cilíndrico y se calculó el módulo Y con la ecuación (7):

$$Y = \frac{P(1-\mu^2)}{2aD} \tag{7}$$

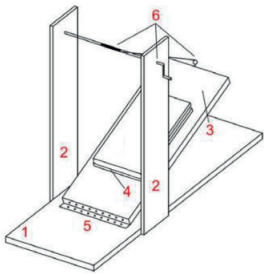
donde P es la carga, μ es el coeficiente de Poisson, para el cual se utilizó un valor de 0.4 extraído de literatura [16], a es el radio de la celda, y D es el desplazamiento de la misma.

2.2 Distribución de tamaño y forma de partícula

Para determinar la distribución de tamaño de los granos, se utilizó el software de análisis de imagen *ImageJ*, el cual permite determinar dimensiones tales como el perímetro y la superficie de cada cara. Se tomaron fotografías de una muestra representativa de granos de maíz y se obtuvieron las dimensiones correspondientes. Con estos datos se calculó la distribución de tamaño en masa en función del diámetro de esfera equivalente.

2.3 Determinación de los coeficientes de fricción

El coeficiente de fricción partícula-entorno se determinó mediante un ensayo de deslizamiento utilizando un equipo construido ad-hoc (Figura 1). Este cuenta con un plano inclinable, sobre el que se fija una placa del material de entorno elegido (plástico y metal), permitiendo determinar el instante y el ángulo para el cual comienza el deslizamiento.



1. Plataforma horizontal
2. Columnas laterales.
3. Plataforma inclinable.
4. Lámina/s del material de entorno.
5. Bisagra.
6. Mecanismo de elevación.

Fig. 1. Esquema del equipo utilizado para determinar el coeficiente de fricción.

Luego de posicionar una partícula (germen hacia arriba o hacia abajo), el plano fue inclinado hasta observar el deslizamiento de la misma. Los ensayos se replicaron 40 veces y se registraron con una cámara de alta precisión, para luego procesar las grabaciones en el software de análisis de video *Tracker* e identificar el instante exacto en el que se inició el movimiento. El ángulo de inclinación (θ_ω) se obtuvo mediante el programa *ImageJ* y se calculó el coeficiente de fricción (μ_ω) utilizando la ecuación (8):

$$\mu_\omega = \tan(\theta_\omega) \tag{8}$$

2.4 Medición del ángulo de reposo estático

Para determinar el ángulo de reposo se emplearon dos métodos. El primero consistió en llenar un embudo plástico, que luego se vació sobre una superficie del material elegido. En el segundo caso, se llenó un cilindro de PVC y luego se elevó a velocidad constante accionando un eje conectado a un motor para su vaciado. En ambos métodos, el ángulo se determinó procesando imágenes de las pilas formadas (Figura 2) con *ImageJ*.

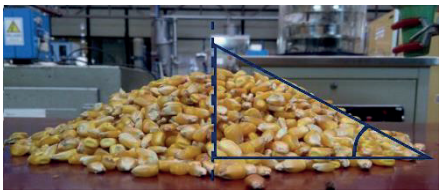


Fig. 2. Medición experimental del ángulo de reposo de granos de maíz a partir del método del embudo.

2.5 Determinación del coeficiente de restitución

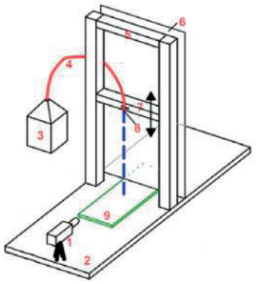
El coeficiente de restitución partícula/entorno se determinó a partir de ensayos de caída libre. Se empleó un equipo construido ad-hoc (Figura 3) que permite generar colisiones controladas entre la partícula y una placa del material entorno elegido (madera, plástico o metal). Cada colisión fue registrada con una cámara de alta precisión, para luego determinar la altura alcanzada por la partícula utilizando el software *Tracker*. A partir de estos datos se calculó el coeficiente de restitución (e) aplicando la ecuación (9):

$$e = \frac{v_{1-}v_2}{u_{1-}u_2} \tag{9}$$

donde u y v son las velocidades inmediatamente antes y después del impacto, y los subíndices 1 y 2 identifican a los elementos involucrados. Considerando que el subíndice 1 hace referencia a la partícula y el subíndice 2 a la superficie plana, las velocidades u_2 y v_2 pueden considerarse nulas y asumir que la energía correspondiente se conserva. Entonces, el coeficiente de restitución e puede calcularse mediante la ecuación (10):

$$e = \frac{v_1}{u_1} = \sqrt{\frac{H_1}{H_0}} \tag{10}$$

donde H_1 y H_0 son la altura máxima y la altura inicial de la partícula en la colisión.



1. Cámara.
2. Plataforma de madera.
3. Bomba de vacío.
4. Manguera.
5. Marco fijo de madera.
6. Placa de fondo.
7. Barra móvil.
8. Partícula muestra.
9. Placa del material entorno.

Fig. 3. Esquema del equipo utilizado para determinar el coeficiente de restitución.

Por otro lado, el coeficiente de restitución intergranular e_a se determinó mediante el método del doble péndulo, utilizando el mismo equipo. Este método permite generar una colisión controlada entre dos partículas pendiendo de hilos a una altura dada [9].

El procedimiento consistió en suspender una partícula A a una altura h_{A1}, formando un ángulo α_{A1}, y dejar que caiga de modo que colisione con la partícula B, suspendida a una altura h_{A2} en un ángulo nulo. Después de la colisión, la transferencia de energía acelera la partícula B y esta se balancea hasta un ángulo de desviación α_{B2}. Las colisiones se registraron con la cámara digital de alta precisión y luego se analizaron con el software Tracker para identificar los ángulos correspondientes. Finalmente, se calculó el coeficiente de restitución empleando la ecuación (11):

$$e_a = \sqrt{\frac{1 - cos(\alpha_{A2} + \alpha_{B2})}{1 - cos\alpha_{A1}}} \tag{11}$$

donde α_{A1} y α_{A2} son el ángulo de desviación inicial y el ángulo máximo que corresponden a la partícula A, mientras que α_{B2} es el ángulo de desviación máximo de la partícula B.

2.6 Calibración del coeficiente de fricción intergranular

El coeficiente de fricción maíz-maíz se calibró replicando en Rocky DEM los dos ensayos de medición del ángulo de reposo. Primero, se realizaron simulaciones para ajustar los parámetros generales y la configuración del sistema. Luego, se llevaron a cabo sucesivas simulaciones modificando el coeficiente hasta lograr que los ángulos resultantes fueran semejantes a los experimentales. Tras calibrar el coeficiente con ambos sistemas, se repitieron las simulaciones intercambiando los valores obtenidos para verificar su validez y elegir el más adecuado.

2.7 Estudio de sensibilidad de los parámetros de rotura

Se realizaron ensayos de rotura de granos individuales de maíz, empleando el texturómetro descripto en la sección 2.1. Este ensayo se implementó en Rocky DEM a fin de ajustar los parámetros del modelo de Tavares [10]. El software requiere la definición por parte del usuario de los siguientes parámetros ya mencionados: σ^2, E_{max}/E_{50}, E_{min}, E_{∞}, d_0, γ, φ, A, b', así como también el modelo de distribución de fragmentos generados.

Se analizaron los valores de los parámetros desconocidos y sus rangos para diferentes materiales en la bibliografía. Una vez identificados, se procedió a realizar sucesivas iteraciones, modificando el valor de un parámetro por vez (análisis de sensibilidad). Luego, se realizaron simulaciones combinando variaciones de los parámetros de interés simultáneamente. Finalmente, se analizaron los resultados y se identificó el conjunto de parámetros que brinda resultados más cercanos a los experimentales (ajuste de parámetros).

3 Resultados

3.1 Forma de partícula y distribución de tamaño en masa

Debido a que los granos de maíz poseen una forma irregular, se deben modelar con formas aproximadas para poder implementar en el programa de DEM los fenómenos y procesos que los involucran. Tras de evaluar diversas geometrías ofrecidas por el programa, se optó por emplear el *Polyhedron* (Figura 4). En simulaciones preliminares, se comprobó que al utilizar esta partícula el tiempo de cómputo es razonable y los resultados que se obtienen son adecuados. Luego se procedió a determinar la distribución de tamaño de partícula (PSD) para incorporarla en el programa. La PSD se calculó utilizando datos experimentales.

Rocky DEM ofrece diferentes alternativas para definir el tamaño de la partícula. Se optó por el diámetro de esfera equivalente, debido a que su cálculo es simple y brinda buenos resultados. El mismo fue calculado a partir del volumen de un paralelepípedo virtual con el espesor, alto y largo de los granos, determinándose una PSD de ocho clases (Tabla 1).

Tabla 1. Distribución de tamaño en masa.

Diámetro (mm)	% Acumulado	Diámetro (mm)	% Acumulado
7.11	0.36%	9.97	72.50%
7.68	4.21%	10.55	92.99%
8.26	13.49%	11.12	96.87%
8.83	27.32%	11.70	100.00%
9.40	50.45%		

El programa genera partículas cuyo volumen es aquel correspondiente a una esfera del mismo diámetro equivalente. Este hecho permite modificar libremente los parámetros que

definen las dimensiones de las partículas sin afectar la masa de cada grano. Se ajustó el *Vertical Aspect Ratio* y el *Horizontal Aspect Ratio* de modo tal que la altura y ancho de la partícula coincidan con los valores experimentales. Se definió el número de esquinas y el grado supercuadrático teniendo en cuenta, además de la forma real de la partícula, la facilidad de cómputo. En la Tabla 2 se presentan los valores finales de los parámetros:

Tabla 2. Parámetros de forma de las partículas simuladas en Rocky DEM.

Relación de aspecto vertical	Relación de aspecto horizontal	Número de esquinas	Grado supercuadrático
1.60	0.70	60	10

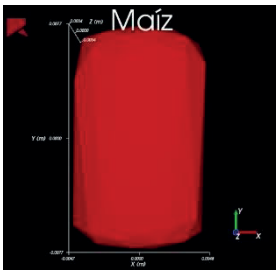


Fig. 4: *Polyhedron* con las propiedades finales.

3.2 Densidad y módulo de Young

Para determinar la densidad del maíz mediante picnometría, se realizaron 10 repeticiones y se promediaron los resultados. El valor experimental resultante es de 1231 kg/m^3 el cual es similar a aquellos valores reportados en la bibliografía para granos de maíz [6], [11].

En cuanto al módulo de Young, este se determinó promediando los resultados de 20 repeticiones de los ensayos de compresión, empleando 20 muestras diferentes. El valor promedio obtenido es de 16.91 MPa, el cual es cercano al rango reportado en la bibliografía [11], [12], [13]. En la Tabla 3 se detallan los resultados finales de cada experiencia.

Tabla 3. Propiedades del maíz obtenidas experimentalmente.

	Densidad (kg/ m^3)	Módulo de Young (MPa)
Media	1231.09	16.91
Coeficiente de variación	3.92%	7.96%

3.3 Coeficiente de fricción μ_ω

En la Tabla 4 se presentan los resultados obtenidos mediante los ensayos de deslizamiento.

Tabla 4. Coeficientes de fricción obtenidos experimentalmente.

	μ_ω maíz/metal	μ_ω maíz/plástico
Media	0.419	0.637
Coeficiente de variación	16.35%	30.05%

Se obtuvo un valor promedio global de 0.419 para el coeficiente de fricción maíz/metal. Este valor es próximo al de 0.476 reportado por Chung et al. [15]. Por otro lado, el valor promedio hallado para el coeficiente de fricción maíz/plástico es de 0.637. Este valor se encuentra dentro del rango reportado en la bibliografía para distintos tipos de plástico [15].

Para calcular los coeficientes, se promediaron todos los resultados conjuntamente, ya que no se evidenció una variación relacionada con la posición de los granos.

3.4 Ángulo de reposo

Para determinar el ángulo de reposo se realizaron 10 repeticiones de cada uno de los ensayos y se promediaron los resultados. En la Tabla 5 se presentan los resultados finales.

Tabla 5. Ángulos de reposo del maíz obtenidos experimentalmente.

	Angulo de reposo (°) –embudo	Angulo de reposo (°) –cilindro
Media	29.96	17.61
Coeficiente de variación	3.81%	7.50%

En el caso del método del embudo, se obtuvo un valor promedio de ángulo de reposo estático de 29.70°. Este valor se encuentra en el rango usual reportado en la bibliografía para diferentes tipos de granos [13], [16].

En el caso del método del cilindro, el valor promedio resultante es de 17.95°. Este valor es considerablemente menor al obtenido mediante el primer método y, a su vez, es similar al valor de 18.11° hallado mediante el mismo método por Shi et al. [17].

3.5 Coeficiente de restitución *e*

A partir de los resultados de los ensayos de caída, se calcularon los tres coeficientes de restitución partícula/entorno. En la Tabla 6 se presentan los valores obtenidos.

Tabla 6. Coeficientes de restitución obtenidos experimentalmente.

	e maíz/madera	e maíz/plástico	e maíz/metal
Media	0.550	0.517	0.457
Coeficiente de variación	26.04%	18.01%	26.64%

El valor promedio de coeficiente de restitución más elevado resultó ser el correspondiente al sistema maíz/madera, mientras que el valor más bajo se obtuvo con el sistema maíz/metal. Este último, si bien es inferior al valor de 0.61 reportado en la bibliografía [6], resulta razonable para el sistema de trabajo. Por otro lado, el coeficiente de restitución intergranular resultante fue de 0.95. Dado que este valor resulta demasiado alto comparado con reportados en la literatura y que su determinación experimental es compleja, se decidió descartar el valor medido y tomar el reportado por Gonzalez-Montellano et al. [6]

3.6 Calibración del coeficiente de fricción intergranular

La medición experimental de esta micro propiedad para granos de maíz, que presentan tamaños y formas irregulares, resulta poco precisa. Es por ello que se decidió calibrar el coeficiente de fricción intergranular. Se realizaron diversas simulaciones modificando no solo este parámetro, sino también parámetros generales del *solver* para la resolución de los modelos de contacto elegidos.

El tiempo de cómputo promedio en las simulaciones preliminares del ensayo del embudo era de 38 h. Para disminuir este tiempo, se modificó el valor de *Softening Factor*, un parámetro que, si bien reduce efectivamente la duración de las simulaciones, afecta el comportamiento de las partículas a partir de un cierto valor. El valor por defecto del *Softening Factor* es 1, pudiendo tomar valores entre 1 y 0.0001. Empleando un valor de 0.1 se logró reducir el tiempo requerido a 12 h manteniendo resultados similares de ángulo de reposo aunque con ciertas variaciones, aceptables, en el comportamiento de las partículas.

Por otro lado, se observó que las partículas, al terminar de caer por el embudo, continuaban deslizándose hasta el final de la simulación, independientemente del tiempo final elegido para la prueba. Esto dificultó la medición del ángulo de reposo ya que su valor variaba con el tiempo. Es por esto que se procedió a manipular el *Damping Ratio*, un factor de amortiguamiento que modifica las oscilaciones presentes en este tipo de pruebas. El valor por defecto del parámetro es cero, por lo que se realizaron simulaciones variando el mismo en un rango de 0.1 a 0.4. Con un *Damping Ratio* de 0.3 se logró reducir considerablemente la variación del ángulo de reposo en el tiempo, logrando una reproducción de la simulación similar al experimento real.

Una vez ajustados los parámetros, se efectuaron múltiples simulaciones modificando sólo el coeficiente de fricción. En la Tabla 7 se resumen los resultados de algunas de estas simulaciones. El ángulo de reposo obtenido experimentalmente es de 29.7°, por lo que el valor de coeficiente de fricción de 0.31 brinda los resultados más cercanos a la realidad.

Empleando los mismos ajustes efectuados para el sistema del embudo, se implementó el ensayo de ángulo de reposo con el cilindro. Se verificó que los resultados al usar diferentes valores de *Damping Ratio* y *Softening Factor* fueran apropiados y se procedió a simular variando el coeficiente de fricción. En la Tabla 7 se presentan resultados seleccionados de las simulaciones finales. El ángulo de reposo experimental correspondiente al ensayo del cilindro es de 17.9°, por lo tanto, el coeficiente de fricción calibrado para este sistema es de 0.25. Las simulaciones, en ambos sistemas, evidenciaron que el ángulo de reposo aumenta al incrementarse el coeficiente de fricción, cumpliendo con lo esperado.

Tabla 7. Valores de ángulo de reposo obtenidos con diferentes coeficientes de fricción intergranular utilizando el embudo y el cilindro.

Sistema del embudo		Sistema del cilindro	
Coeficiente de Fricción	Angulo de Reposo (°)	Coeficiente de Fricción	Angulo de Reposo (°)
0.32	30.16	0.17	14.43
0.315	30.82	0.22	17.09
0.31	29.41	0.25	17.99

Por último, a fin de verificar los resultados, se utilizó el coeficiente de fricción de 0.31 en el sistema del cilindro y se obtuvo un ángulo de reposo de aproximadamente 23°, un valor 30% mayor que el experimental. En cambio, empleando el valor de 0.25 en el sistema del embudo, resultó que las partículas no terminan de caer quedando atascadas en el cuello del embudo, lo cual no es representativo de la realidad. Es por ello que se consideró como resultado final de la calibración el valor de 0.31.

La Figura 5 muestra imágenes de los sistemas simulados en el programa.



Fig. 5. Implementación del experimento de medición de ángulo de reposo en Rocky DEM con el sistema del embudo (izq.) y con el sistema del cilindro (der.).

3.7 Estudio de sensibilidad de parámetros de rotura

En primer lugar, se analizó el efecto de los diferentes parámetros del modelo de Tavares, identificando aquellos que más efecto generan sobre la rotura. Luego, se implementó en Rocky DEM el experimento de rotura de granos individuales realizado en el texturómetro, utilizando los parámetros y propiedades del material medidos y calibrados previamente. Las simulaciones de calibración de los parámetros de rotura se describen a continuación.

Usualmente, el parámetro E_{min} mantiene el valor predeterminado de 1. Por lo tanto, se verificó que variar su magnitud no afecta los resultados de las simulaciones. Asimismo, modificar el parámetro E_{∞} tampoco altera los resultados de la rotura, ya que no influye en la forma en que se rompe la partícula. Se observó que aumentar el valor de E_{∞} retrasa el momento en el cual ocurre la rotura, ya que implica más energía para romper la partícula. Finalmente, se optó por mantener los valores predeterminados de estos parámetros.

En cuanto a los parámetros d_0 y σ^2, al modificar sus valores se observó que no influyen perceptiblemente en la rotura ni en el tiempo que tardan las simulaciones. Nuevamente, se decidió conservar los valores por defecto de ambos.

Por otro lado, se realizaron simulaciones con diversos valores de φ y se comprobó que este parámetro no afecta la forma en que se rompe la partícula. Sin embargo, para valores superiores o iguales a 1 la rotura no ocurre, por lo que se mantuvo el valor de 0.45.

Tras definir los parámetros mencionados, se efectuaron simulaciones modificando valores de A y b', dos parámetros relacionados directamente con la fragmentación. En la Figura 6 se muestra la variación del número de fragmentos generados en la rotura en función de A, y en la Figura 7, el mismo análisis en función de b'.

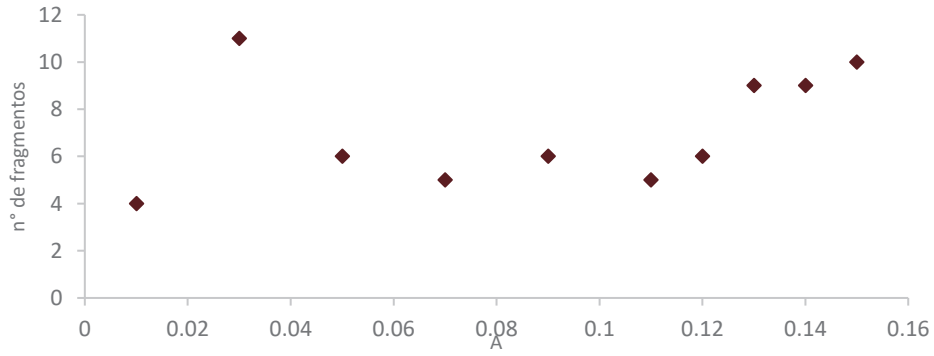


Fig. 6. Variación del número de fragmentos en función del parámetro A.

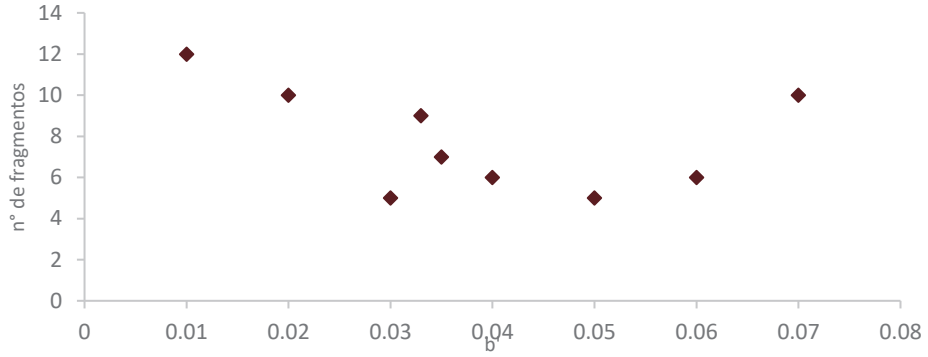


Fig. 7. Número de fragmentos en función del parámetro b'.

Se puede observar que el número de fragmentos tiende a aumentar al incrementarse el valor de A, lo que se corresponde con la definición del parámetro. El valor de b' no guarda relación con la cantidad de fragmentos, la cual oscila, e incluso varía al repetir una misma simulación. Debido a esto, se decidió mantenerlo en su valor predeterminado de 0.033.

En la mayor parte de los ensayos experimentales de rotura del maíz, se obtuvieron dos fragmentos de tamaño similar. Tal como se observa del análisis de sensibilidad, al simular esta experiencia en Rocky DEM, el número de fragmentos obtenidos siempre fue mayor. Utilizando un valor de A de 0.01, sin embargo, se logró que la partícula se fragmente en cuatro, lo cual es relativamente cercano a la realidad y se consideró aceptable considerando que el modelo de rotura implementado en Rocky se encuentra desarrollado para múltiples partículas en simultáneo y no la rotura individual como el caso de estudio.

4 Conclusiones

La determinación de las propiedades de los granos de maíz (densidad, módulo de Young ángulo de reposo, coeficiente de fricción partícula/entorno, coeficiente de restitución partícula/entorno) se logró exitosamente mediante el diseño y construcción de dispositivos experimentales, obteniendo valores cercanos a los reportados en la literatura. Además, se pudo obtener una distribución de tamaño de partícula adecuada e identificar una forma geométrica aproximada apropiada para representar los granos de maíz en Rocky DEM.

Por otro lado, se llevó a cabo la implementación de las experiencias de ángulo de reposo y de rotura de una partícula para la calibración de los parámetros restantes. Se logró calibrar el coeficiente de fricción intergranular, obteniéndose un valor de 0.31 para el caso de estudio, que permite reproducir exitosamente el comportamiento real del material. Por último, tras realizar un análisis de sensibilidad detallado, se consiguió ajustar los parámetros del modelo de rotura de Tavares que reproducen de manera aceptable la rotura individual de granos de maíz observada experimentalmente.

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The time-lagged effect problem on (un)truthful data, a case study on COVID-19 outbreak*

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Abstract. The Coronavirus SARS-CoV-2 (COVID-19) emerged by December 2019, in Wuhan, China; it was reported and, a few months after, in the most of countries we are living a pandemic of an (almost) unknown disease never observed before. For this reason, the importance of a good measurement on the counting of observed cases has a crucial role. This work addresses the time-lagged effect problem via Bayesian analysis supported by a stochastic discrete-event simulation to give an answer to the truthfulness of the data and to validate the obtained results in terms of proportions based on an expected result in the particular case of Spain. Obtained results show that the reported data is untruthful and can make wrong any analysis, but even when the simulating results are as we expected they might be wrong in terms of absolute numbers. However, the most important knowledge we get is related to the fact that the disease might be considered under control because it is more likely that a person gets recover than She/He dies.

Keywords: Bayesian analysis · Stochastic simulation · COVID-19

1 Introduction

The Coronavirus SARS-CoV-2 (COVID-19) emerged by December 2019, in Wuhan, China. It was reported and, a few months after, in the most of countries we are living a pandemic of an (almost) unknown disease never observed before. Despite the drastic, large-scale containment measures promptly implemented by the Chinese government, in a matter of a few weeks the disease had spread well outside China, reaching countries in all parts of the globe [4] resulting in human and economical crisis in most of them.

To decrease the damage associated with COVID-19, public health and infection control measures are urgently required to limit the global spread of the disease [18], but till now the ongoing pandemic seems not to be overcame unless a vaccine appears. However, the saying: *you cannot manage what you do not*

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measure, and, therefore, the importance of a well measurement on the counting of observed cases has a crucial role. On this way, the World Health Organization (WHO) [21] has published that the number of real infected individuals are between 10 and 20% of the real ones. Even so, Ioannidis [7] reviews and comments the possibility of a problem that spread even faster than the pandemic, the reliability on data; which results on a clear issue that makes models useless.

So, how COVID-19 pandemic behaves throughout time? this question might be the most important to find an answer for (as soon as possible) in the last time. On this way, it is important to anticipate the number of new cases on a daily-basis to take care about healthcare systems as well as the budget to dedicate to this disease. Several authors has been addresses this question using different models, but the most used has been those ones with dynamic nature such as the Susceptible-Exposed-Infected-Removed (SEIR) model [13,5], Susceptible Un-quanrantined infected, Quarantined Infected, Confirmed infected (SUQC) model [25], Susceptible Exposed Infected Isolated with treatment Removed (SEIJR) model [16,14], Exponential growth model [24,9], Stochastic simulations of outbreak trajectories [15] and Hierarchical models [3]. Nevertheless, despite of the possibility of working with non-reliable data approximations to transition rates, in the case of dynamic models, as the infection rate, mortality rate and recovery rate has been computed.

This study aims to merge prior knowledge generated at the moment, using the particular case of the observed data in Spain gathered from the Github repository associated with the interactive dashboard hosted by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University, Baltimore, USA [8], to know the real number of confirmed cases that would be by using Bayesian Analysis assuming the counting cases behave as a Poisson process to fit the necessary parameters to make a simulation throughout Discrete Markov Chains within a specific period.

This work is organized as follows: Section 2 establishes the time-lagged effect problem performing a descriptive analysis of the data and then makes the statement of the problem under study. Section 3 shows a Bayesian approach to fit the necessary random variables considering a hypothesis test on the lagged time effect. Section 4 addresses the truthfulness of the data via a stochastic discrete-event simulation to give an answer to the truthfulness of the data and to validate the obtained results in terms of proportions based on an expected result. Finally, Section 5 gives the main insights we found and propose to escalate the problem under study.

2 The time-lagged effect problem

In this section, we perform a descriptive analysis of the counting of each kind of cases in order to motivate the discussion and the way we model the situation that apparently we see. Then, we formally declare the variables in the situation and the equation that support the behaviour through dynamic modelling in its discrete version.

2.1 Descriptive analysis

From the considered data source, we can recognize that there was an inflexion point before and after a lock-down was established in most of the countries which take that measure. In the particular case of Spain, the lock-down policy was taken in March 14th, and as far as we know the expected effect of this measure was around two weeks after that, by March 28th, an inflexion point must appear on the counting. Motivated on this *belief*, we will work with the data corresponding to March and April given two main reasons: i) these months correspond to the most chaotic in term of how the counting was conducted, and also in this particular country, the beginning of the pandemic; and ii) to consider a larger period would add noise related to the effect of the lock-down on how the disease spread. Fig. 1 shows the counting in both months by each kind of case, Confirmed, Recovered and Death cases and two vertical lines that indicate both the day at lock-down was and the expected effect.

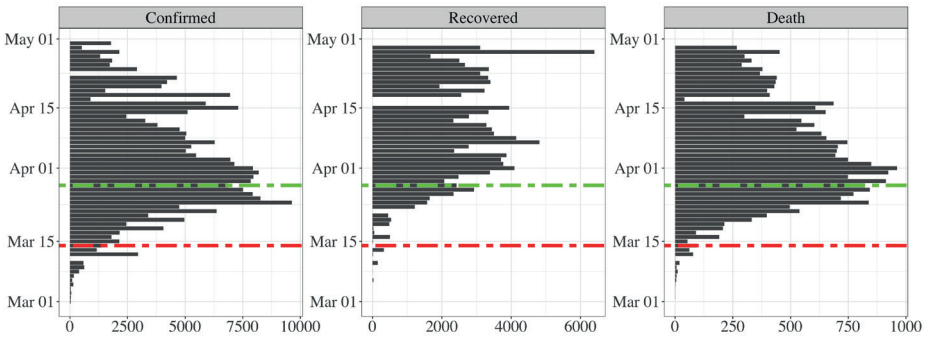

Fig. 1: Counting during March and April by each kind of case, Confirmed, Recovered and Death cases. The vertical lines indicate the day at the lock-down was implemented (March 14th, in red) and at the day its expected effect was (March 28th, in green).

It is clear to see that the counting for each kind of case, the so-called curves, do not follow a strict pattern, which can be explained, discarding the lock-down, by the manner, the authorities performed the counting. It affects directly on the Confirmed cases and therefore on Recovered and Death cases, which would show a similar -proportional- pattern after a time to recover or to die.

The later mentioned effect can be supported numerically by the descriptive statistics shown in Table 1. In the case of Confirmed cases, we see that the counting from March to April did not change as much as Recovered and Death cases, where they were (almost) four and two times greater, respectively. However, two simple ways to recognize this effect could be:

– Taking into account that a person must be a Confirmed case before be a Recovered or Death case, if we move these two counting curves some days,

they should fit with the counting related to Confirmed cases, which often happens.
– The sum of Recovered and Death cases is lower than the sum of Confirmed cases during the period we are working with.

this informal evidence allows us to motivate the problem formally.

Table 1: Descriptive statistics of the COVID-19 pandemic behaviour during March and April of 2020. Total number of Confirmed, Recovered and Death cases are 225,166, 112,048 and 24,543 people, respectively.

	Confirmed		Recovered		Death	
	March	April	March	April	March	April
Count	104,034.00	121,132.00	22,645.00	89,403.00	9,387.00	15,156.00
Q1	286.50	1,909.25	0.00	2,517.25	7.00	369.75
Mean	3,355.94	4,037.73	730.48	2,980.10	302.81	505.20
Median	2,162.00	4,423.00	53.00	3,256.00	94.00	489.00
Q3	6,621.50	5,425.25	1,396.00	3,655.25	628.50	679.00
SD	3,256.35	2,238.22	1,050.14	1,346.84	344.78	222.43

2.2 Statement of the problem

These so-called curves are dependent on each other where Recovered and Death cases are lagging product of the Confirmed cases, and thereby from another of non-infected people, the Health people.

The problem under study could be characterized by a dynamic modelling point of view. From now on, we will consider four possible states at which people are at certain time t: i) Health, are the people who have never been positive to the disease before; ii) Confirmed, are the people who currently give positive to the disease; iii) Recovered, are the people who are healthy once they gave positive before; and iv) Death, are the people who have died due to the disease. On this way, it is possible to state the following *Once a person is a Confirmed case there are two possible transitions after a certain elapsed time, that person will get recover or will die*, this situation is such as Fig. 2 shows with their respective transitions.

Formally, we can recognize that curves could be characterized by using Poisson processes with different intensities and elapsed times to change from one state to another. Let's denote the set of states $\mathcal{I}$ and the number of people at time t in each state $N_i(t)$, $\forall i \in \mathcal{I}$. Then, we propose that the number of people $N_i(t)$ is defined by a Poisson process with parameter $\lambda_i t_i$, where λ_i represents the number of new cases (in people per day), intensities from now on, and t_i represents the elapsed time necessary to change from one state to another one, $\forall i \in \mathcal{I}$.

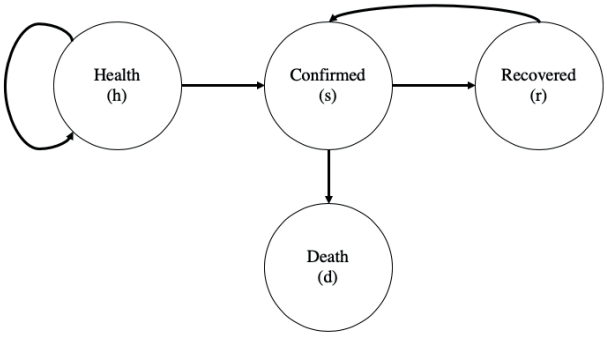

Fig. 2: A general illustration of the dynamic model considering the possibility of the population can get sick again. The states of the model indicate in which category the person is at a certain time t and where She/He from, which is indicated by the arrows.

Thus, considering the elapsed time to get recover or to die as t_r and t_d, respectively, we can define the Poisson processes as Definition 1 shows.

Definition 1 (*Structural equations*). *Let's consider a person who incubates the disease in t_s days. She/He will get recover or die after t_r or t_d days, respectively. Also, be $Y_i(t_i)$ the cumulative number of cases within a certain days in $[t; t + t_i]$, $i \in \mathcal{I}$. Thus, we can define the total number of Recovered and Death cases depending on the Confirmed cases as follows:*

- $Y_r(t_r) = N_r(t + t_r) - N_s(t)$, *defines the number of total Recovered cases in* $[t; t + t_r]$ *such that* $Y_r(t_r) \sim Poisson(\lambda_r t_r)$.
- $Y_d(t_d) = N_d(t + t_d) - N_s(t)$, *defines the number of total Death cases in* $[t; t + t_d]$ *such that* $Y_d(t_d) \sim Poisson(\lambda_d t_d)$.

thus, the equivalence between Confirmed, Recovered and Death cases is given by

$$Y_s(t + t_s) = Y_r(t + t_r) + Y_d(t + t_d) \tag{1}$$

where $Y_s(t + t_s) \sim Poisson(\lambda_s t_s)$ *with parameter* $\lambda_s t_s$ *such that* $\lambda_s t_s = \lambda_r t_r + \lambda_d t_d$.

Finally, since a person is different from each other, both the number of new cases λ_i and the elapsed time necessary to change from one state to another one t_i are not fixed parameters, but random variables. Fig. 3 shows the idea behind Definition 1 where, without loss of generality, the distribution is a smoothed one of the number of people in each state $N_i(t)$ throughout t. Also, it shows distribution at certain day t without the time-lagged effect, where it is expected that the Confirmed cases are equal to the sum over Recovered and Death cases.

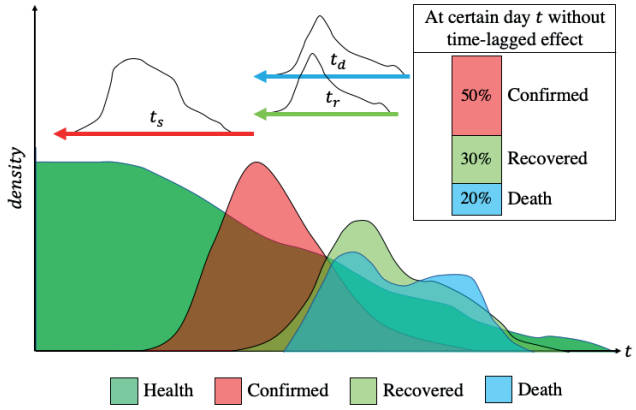

Fig. 3: Illustration of the problem under study. We consider four possible states, where the sum on specific states must be equal to the precedent states, e.g. the density curve that represents the Health people must be equal to the sum over the other density curves without the time-lagged effects t_s, t_r, t_r; which also are random variables.

3 Bayesian analysis

In this section, we propose a way to overcome the variable fitting via Bayesian Analysis using the package RStan [19]. We state the prior distribution for the later mentioned parameters and perform an interesting hypothesis test related to whether the number of days to change from Confirmed state to another are equal.

3.1 Prior distributions

As we state in Definition 1 before, the parameters that are involved in Expression (1) are random variables, and to fit them we propose a Bayesian way. On this way, we need to provide priors distributions which draw the knowledge at the moment. These could be obtained from our own knowledge or using other novel researches who also addresses similar problems from an epidemiological point of view.

The case of the intensities (λ_i) is highly dependent on the policies and at which moment they were implemented, so we adopt the knowledge based on how we believe the curves grow throughout time in these two months. Consequently, as intensities represent the number of people in each state at certain day t, it makes sense to think in a Gamma distribution.

On the other hand, the response against the disease has been studied by several authors which report what they found. The literature review shows that the elapsed times t_i distribute as a Gamma for each one of them. The incubation time, t_s, is a Gamma with mean 6.5 days and standard deviation of 2.6 days

[22,2]; the elapsed time to get recover, t_r, is a Gamma with mean 10 days but can be up to 14 or 21 days [17]; and the elapsed time to die, t_d, is a Gamma with mean 20 days and standard deviation equal to 10 days [22].

We use such parameterization of the Gamma distribution with expectation defined by $\mathbb{E}(x) = \alpha/\beta$ and variance $Var(x) = \alpha/\beta^2$; where α and β parameters, obtained by solving a system of equation, are shown in Table 2.

Table 2: Parameters that define the Gamma distribution based on the prior knowledge for each random variable to fit.

	λ_s	λ_r	λ_d	t_s	t_r	t_d
α	250	122.50	2.50	26.20	5.00	126.49
β	4.03	0.50	6.32	4.03	0.50	6.32

3.2 Posterior distributions

Once we already state the prior distributions, we can get the posterior distributions that will show the merge between the prior knowledge and the data. Table 3 shows descriptive statistics from the obtained results, where the $\hat{R}$ statistic shows the fitting process was successfully achieved, and the confidence intervals are not too large respect to the mean. These results are saying that:

- The incubation time, t_s, is about 18 days but can be between 16 and 19 days. The elapsed time to get recover, t_r, is about 11 days but can be up to 9 and 13 days. The elapsed time to die, t_d is 20 days with possibilities to find cases from 17 to 23 days.
- The number of daily Confirmed cases, λ_s is in mean 5,888. The number of daily Recovered cases, λ_r is 3,500. The number of daily Death cases, λ_r is 521.

Table 3: Descriptive statistics for fitted posterior distribution. Notice that the mean and percentile values have been truncated to enhance their interpretation. The $\hat{R}$ statistic shows the fitting process was successfully achieved.

	Mean	Error	5%	95%	$\hat{R}$
t_s	18	0.03	16	19	1.00
t_r	11	0.04	9	13	1.00
t_d	20	0.06	17	23	1.00
λ_s	5,888	306.86	5398	6408	1.00
λ_r	3,500	308.45	2993	4008	1.00
λ_d	521	1.65	452	607	1.00

A graphical analysis of the obtained results can be carried out to see the effects of the selected data which are set out in Fig. 4. It shows the density plot for each posterior distribution. In this, it is possible to distinguish that, although the prior distributions for the elapsed times are evidence from other works, and might be considered informative ones due to their short variances, the data change the landscape in its favour. The most important insight of the results is such a person who gave positive to the disease, it is more likely that She/He gets recover due to a temporal reason. Also, the number of daily Confirmed cases is greater than the Recovered cases which are greater than the Death cases.

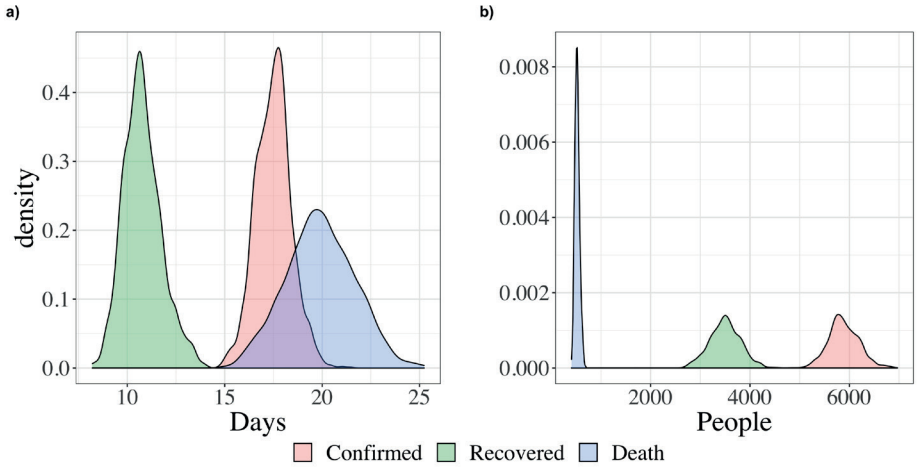

Fig. 4: Density plot for each posterior distribution of elapsed times and intensities. **a)** shows the number of days to change from one state to another and **b)** shows the number of daily cases in mean.

3.3 Differences on the elapsed times in the transitions from Confirmed cases

An interesting and useful question corresponds to check some conditions of the dynamic, in this particular case whether the number of days to change from Confirmed state to another are equal, in other words, whether the elapsed time to get recover (t_r) is equal to the elapsed time to die (t_d). Taking into account the Definition 1, it is equivalent to the hypothesis test given by

$$H_1 : Y_s(t + t_s) \sim Poisson(\lambda_r t_r + \lambda_d t_d)$$
$$H_2 : Y_s(t + t_s) \sim Poisson((\lambda_r + \lambda_d)t)$$

where the probability of each hypothesis to be true is

$$Pr(H_i|y) = \frac{\pi(H_i)Pr(y|H_i)}{Pr(y)} \tag{2}$$

again, as we are working from a Bayesian point of view, we need a prior probability for each one of the hypothesis.

The literature review did not reveal an answer for this question, but the Bayesian point of view allow us to state a non-informative probability to give to the data an important role. Thus, we use the most non-informative probability, 50%. Doing so, the hypothesis test does not support any of them, indeed the probability to be true for each hypothesis is equal to 50%, it means that there is no difference on the elapsed times in the transitions from Confirmed cases and it is completely at random.

4 Stochastic discrete-event simulation

At the moment, we have proposed the equation and parameters that would enable us to analyze the behaviour of the pandemic. Nevertheless, a crucial question arises and it is still an open problem to overcome. Are we working with (un)truthful data?. We show an approach based on a stochastic discrete-event simulation using Markov Chains to give an answer and validate the results obtained previously as an underlying product.

4.1 State equations

First of all, following the dynamic such as we showed in Section 2 and considering the elements given in Definition 1, we can establish a stochastic Markov Chain and the state equations that define it to address a discrete-time simulation.

Let $x_{i,j}(t)$ be the transition rate from state i to state j at time t and $N_i(t)$ be the people in state i at time t, $\forall i, j \in \mathcal{I}$. Thus, for a certain time $t \geq max\{t_r, t_d\}$, the elapsed time to get recover or to die, respectively, the state equations are defined by:

$$N_h(t+1) = x_{h,h}(t)N_h(t) - x_{h,s}(t)N_h(t-t_s) \tag{3}$$

$$\begin{aligned} N_s(t+1) = {} & x_{h,s}(t)N_h(t-t_s) + x_{r,s}(t)N_r(t-t_s) \\ & - x_{s,r}(t)N_s(t-t_r) - x_{s,d}(t)N_s(t-t_d) \end{aligned} \tag{4}$$

$$N_r(t+1) = x_{s,r}(t)N_s(t-t_r) - x_{r,s}(t)N_r(t-t_s) \tag{5}$$

$$N_d(t+1) = x_{s,d}(t)N_s(t-t_d) \tag{6}$$

this system of equations enables us to simulate the dynamic considering the whole results obtained previously. Equation (3) defines the number of people in Health state at time $(t+1)$ by considering the number of people who were in this state at time t minus the people who incubate the disease at $(t-t_s)$, i.e. since t_s days the person got infected. Equation (4) establishes that the Confirmed Cases at $(t+1)$ is equal to the people who got infected t_s days but never had been in Confirmed state before, and the people who got infected t_s days ago but those ones that at least have been in Confirmed state before, i.e. those people who incubate the disease again; minus the people who get recover since they were a

Confirmed case and the people who die. Equation (5) considers the difference between the people who get recover, taking into account that they have been considered as Confirmed cases previously, and those people who incubate the disease again after they got to recover. Finally, Equation (6) shows the Death state as and absorbing one.

4.2 Implementation, results and their validation

Algorithm 1 shows the implementation of the simulation which aims to compute the number of people at each state $i \in \mathcal{I}$ within a defined period $[t; \hat{t}]$ until the entire population incubate the disease (line 1). It works with the posterior distribution for each parameter as known data, and involve the stochastic component where it makes the intensities sampling for each state $i \in \mathcal{I}$ (line 2-3) and where it makes the difference over the elapsed times to get recover or to die according to a uniform $(0, 1)$ random number (line 4-10). Finally, it performs the simulation by using the state equation defined previously (line 11) at repeat for time $(t + 1)$ (line 12).

Algorithm 1: Stochastic discrete-event simulation

Data: Population, simulation period, posterior distribution of intensities and elapsed times, transition rates and hypothesis test probabilities.
Result: Number of people at each state within a defined period.

```
1  while Population > 0 and t ≤ t̂ do
2      for i ∈ ℐ do
3          get a sample λ̂_i from λ_i
4      get a sample t̂_s from t_s
5      u ← runif(1)
6      if |u − Pr(H_1|y)| < |u − Pr(H_2|y)| then
7          for j ∈ ℐ {s} do
8              get a sample t̂_j from t_j
9      else
10         get a sample t̂_{r+d} from t_r ∪ t_d
11     Perform the state equation
12     t ← t + 1
```

Till now, we already have the almost all parameters we need in order to carry out the later mentioned simulation except for the transition rates values and the number of people in the country. Fortunately, the last value can be obtained from the National Institute of Statistics (INE) [6]; and the transition rates have been reported in epidemiological researches. Velavan and Meyer [20] report the infection rate is 2.2% in average, whereas Anastassopoulou et al. [1] get it is between 1.9% and 1.92%. Zhonghua Liu Xing Bing Xue Za Zhi [26]

shows that the mortality rate is equal to 0.3% among the health workers who have become infected and Lai et al. [11] report it decreases from 2.5% to 2% between February 12th and February 14th, when the confirmed cases reached 66,576 globally [23]; finally Yi et al. [23] report a recovery rate of 87%. In the case of the transition rate of incubating the disease again after they got to recover, the literature review has not to evidence about it [12,10].

Thus, considering the whole data mentioned previously, including the posterior distributions for each fitted random variables, we can perform the stochastic discrete-event simulation. The obtained results for the number of people in each state are: i) Confirmed cases are 18,095,738; ii) Recovered cases are 12,048,823; and iii) Death cases are 50,056. These results are different from the reported cases. If we would take the simulation as the true number of people in each state, the reported cases would correspond to a 1.24%, 0.93% and 49.03% for Confirmed, Recovered and Death cases, respectively. However, these last results must be validated.

On this way, as we showed above in particular in Fig. 3, the expected result of the time-lagged effect problem should be such that at some day t the proportion of the cases would correspond to half for Confirmed cases and a half for the sum over Recovered and Death cases, and this must be applied on the reported cases as well as the simulating results to answer the issue related to the truthfulness of the data. Fig. 5 shows a stacked column plot of the proportion of people in each state and a dashed horizontal line is overlapped at the middle of the plot to enhance the visualization. It is to say that the reported cases do not behave as we expected, especially at the beginning, but the simulation does despite a couple of atypical counting. Therefore, based on the expected result of the time-lagged effect problem the reported cases, and thus the data, should be considered as untruthful data, whereas the simulation was performed on the right way in terms of proportion, but might be wrong in terms of absolute numbers.

5 Conclusion and future works

This work addresses the time-lagged effect problem on the COVID-19 pandemic via Bayesian analysis supported by the stochastic discrete-event simulation to give an answer to the truthfulness of the data and to validate the obtained results in terms of proportions based on an expected result. Motivated by this problem, the reported data of Spain is used as a study case. This reported data was characterized by a graphical approach and from a descriptive statistics point of view, where a simple analysis enables us to recognize the proposed problem is set up in the data.

The way we take to fit the established parameters, and therefore to perform the simulation via Markov Chain, is computationally tractable by a desktop computer. Obtained results show that the reported data is untruthful and can make wrong any analysis, but even when the simulating results are as we expected they might be wrong in terms of absolute numbers.

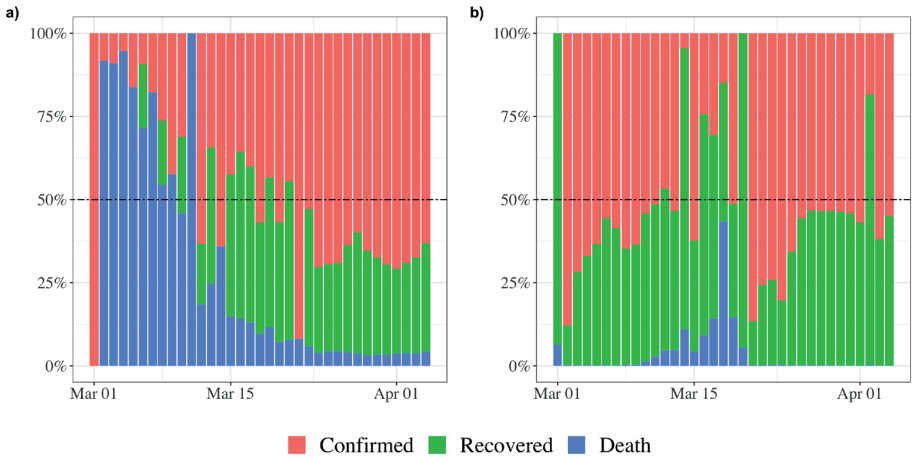

Fig. 5: Validation plot by stacked columns for the proportion of people in each state for **a)** reported cases and **b)** the simulating results. The dashed horizontal line indicates the 50% of the data to enhance the visualization.

However, despite simulating results are correct in terms of absolute numbers or not, they provide useful knowledge of the pandemic behaviour in this particular study case. The most important ones are related to the fact that the disease might be considered under control, because of it is more likely that a person gets recover than She/He dies, and it behaves differently from other countries according to related studies which are used as prior knowledge on the carried out Bayesian analysis. Nonetheless, the number of daily Confirmed cases is greater than the number of Recovered cases which is greater than the number of Death cases.

For future works, we consider making wider the period modelling the transition rates as random variables and to evaluate the effectiveness of the lock-down through a change of point analysis to find a stationary state and when it would be achieved.

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Nuclear Safety Management after Fukushima accident. A systematic and critical review of the state of the art.

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Abstract. This study examines the available evidence about the state of the art of Safety Management in theory and practice applied in particular in the field of the nuclear reactors of the nuclear industry. (1) Background: During the last years, the operation of industrial facilities has advanced towards the integration of the various aspects of its management, mainly driven by the search and achievement of the highest operational performance in a competitive environment. The nuclear industry is no stranger to this movement, with the particular distinction of its main driver: safety in the operation of its facilities; (2) Methods: a systematic review to summarize and critically analyze state of the art on safety management, specialized in the management of nuclear power reactors and nuclear research reactors; (3) Results: out of 405 articles found, twenty-seven studies met the inclusion criteria for the synthesis and qualitative review, in particular, all these articles are about nuclear power reactors; (4) Conclusions: Based on the available evidence, the lack of frameworks and general models and integrators of the specific ones is the main deficiency of the area, where the conceptual, holistic or systematic models are of recent proposal and discussion.

Keywords: Nuclear, Safety, Management, Reactors

1 Introduction

Since its beginning, the nuclear industry has been a pioneer in developing and applying specific safety standards for the care of the worker, the environment, and society, integrating its own operating experience and accidents and that of the conventional industry. In these terms, this industry is considered from its technical performance as an ultra-safe macro-technical system (Amalberti, 2001).

In this sense, the academy has developed various theoretical approaches and models that explain the causes of the most relevant industrial accidents of the modern industrial

era. These approaches have been integrated into the safety requirements and recommendations of the main relevant international and national organizations and mainly by the International Atomic Energy Agency (IAEA). These approaches were systematically integrating the lessons learned in the nuclear accidents that occurred (in Nuclear Power Reactors (NPP): Three Mile Island, 1979; Chernobyl, 1989; Fukushima, 2011. And in Research Reactors (RR) RA-2, 1983. By strengthening and expanding the scope of the domain of the factors that explain an accident and/or safety performance (Acuña et al., 2020).

In particular, this paper identifies and analyzes what specific academic contributions were made during the last decade to safety management in the operation of nuclear reactors, in light of the last nuclear accident that had consequences both on the assets of its operating entity, and in society as a whole (IAEA, 2015).

One of the lessons learned by the nuclear industry from the Fukushima Daiichi nuclear accident was the need to ensure the safety of its facilities with a more integrated approach to the factors that contribute to it (IAEA, 2014; Yang, 2014; IAEA 2015). Some of them being institutional, organizational, technology management and operation factors and human factors. These are included in the stream called Safety Management.

Safety Management (SM) is a relatively new and developing area of formal and multidisciplinary study (Pillay, 2015) that comprises a set of theories and practices on decision-making, resource management, execution of activities and tasks, and the results they achieve (positive or negative), about the safety performance of an industrial asset. These positive or negative results are directly related to the care and preservation of the organization's assets and those of society as a whole and the achievement and maintenance of a certain performance. Therefore, the care and preservation of these assets imply avoiding actions that have irreversible consequences (incidents and/or accidents). This is available from the design stages of the installation and the systems that operate and manage it.

2 Methodology.

2.1 Study Design, Search Strategy and Selection Process

Having considered conducting a systematic review, to carry out the study design, we follow the guidelines proposed by Oliveira et al. (2019). For this purpose, the SM of nuclear reactors was defined as a field study or objective of the survey.

To fulfill this objective, it was decided to use both academic search engines and specialized technical search engines. In this way, the search could be reached in documents published by non-academic publishers and/or presented in specialized conferences of the nuclear industry whose procedures are not academically indexed.

The academic search engines used were Science Direct and Scopus, and the INIS (International Nuclear Information System) of IAEA was used as a technical search engine. INIS "(…) hosts one of the world's largest collections of published information on the peaceful uses of nuclear science and technology. INIS is unique and valuable

information resource, offering global coverage of nuclear literature". This search engine is widely used by academics and practitioners of the nuclear industry, so it was considered relevant.

These search engines were used for articles from peer-reviewed journals, presentations at congresses, and reports (technical documents), as the time window used the last ten full years, that is, from 2009 to 2019. This window and time filter allow us to survey the most recent publications before the Fukushima Daiichi nuclear accident that occurred in 2011 and how the lessons learned in this were incorporated into state of the art. Regarding the keywords used were: (safety management), (nuclear reactor), or (nuclear power plant). At the end of the keyword search, Zotero reference management software was used to select and record titles, abstracts, and full-text articles based on inclusion/exclusion decisions.

Studies were included if, for Scopus search:Contained the keywords "safety" and "management" and "nuclear" and (“reactor” or “plants”) on Title+Abs+Keyboards. And for INIS search: Contained the keywords "nuclear and reactor” on All Words Filter.

Studies were excluded if they: were duplicates, referring to other facilities that are not reactors (e.g., accelerators, medical centers with radiation equipment, radioisotope plants, laboratories that operate radioactive sources). And if it was focused on SM applied on an only structure, system, component, or activity of the nuclear reactor (e.g., fuel, wastes, maintenance) without a vision about the totality of the installation.

2.2 Classification criteria

Considering the preceding paragraphs and the reading and analysis of the articles, five thematic areas were defined to classify the articles according to their contributions.

Criteria to classify the articles are:

- Frameworks and Theories for Safety Management: Articles whose content presents frameworks for addressing SM issues considering the particularities of NPP or makes theoretical statements about it.
- Safety Culture: Articles whose content presents applications or interpretations about Safety Culture as contributors to the understanding or measurement of SM.
- Management systems: Articles whose content presents proposals or cases of application of Safety Management Systems (SMS) at different organizational or institutional levels of an NPP.
- Applied Safety Management: Articles whose content presents case studies, development, or application of tools to implement or measure SM in Nuclear Power Plants.
- Safety Performance: Articles whose content presents different contributions to the application of tools for the measurement or understanding of safety performance.

3 General Results.

When applying the methodology described above, a total of 27 articles were recovered. The table below (Table 1) presents the qualitative synthesis of the articles recovered.

Table 1 Characteristics and summary of documents recovered.

#	Author (year of publication)	Title See Reference List	Country	Type of Document	Thematic Area Classification
1	Hildebrand M., et al. (2009)	[1	Norway	Conference Paper - Human Factors and Ergonomics Society Annual Meeting	Applied Safety Management
2	Kavoliunas M., et al. (2009)	[2	Canada	Professional Report – SAE International	Management Systems
3	Cullen R. (2009)	[3	UK	Conference Paper - Institution of Chemical Engineers Symposium Series	Safety Culture
4	Zhai Z. (2009)	[4]	China	Conference Paper - IEEE IEEM	Frameworks and Theories for Safety Management
5	Wahlström B., Rollenhagen C. (2010)	[5]	Sweden	Conference Paper - International Conference on Operational Safety Experience and Performance of NPPs and Fuel Cycle Facilities	Frameworks and Theories for Safety Management
6	Guldenmund F. (2010)	[6]	Netherlands	Journal Paper - Journal of Risk Analysis	Safety Culture
7	International Nuclear Safety Advisor Group (2010)	[7]	Austria	Professional Report – INSAG - IAEA	Frameworks and Theories for Safety Management
8	Paradies, M. (2011)	[8]	USA	Journal Paper - Process Safety Progress	Applied Safety Management
9	Himanen, R., et al. (2012)	[9]	Finland	Journal Paper - Journal of Risk Analysis	Applied Safety Management
10	Reiman, T., Rollenhagen, C. (2012)	[10]	Sweden	Conference Paper - World congress on Ergonomics - Designing a sustainable future	Frameworks and Theories for Safety Management
11	Shan Z. (2012)	[11]	China	Conference Paper - Probabilistic Safety Assessment and Management	Management Systems
12	Wu Y. et al. (2012)	[12]	China	Conference Paper - International Conference on Automatic Control and Artificial Intelligence	Frameworks and Theories for Safety Management
13	Latorre Navarro, et al. (2013)	[13]	Mexico	Journal Paper - Journal of Safety Research	Safety Culture
14	Wahlström B., Rollenhagen C. (2014)	[14]	Netherlands	Journal Paper - Safety Science	Frameworks and Theories for Safety Management
15	Akselsson R. (2015)	[15]	Sweden	Conference Paper - Conference on Safety and Reliability of Complex Engineering Systems	Management Systems
16	Kouabenan D, et al. (2015)	[16]	France	Journal Paper - Safety Science.	Safety Culture
17	Ruimin M., et al. (2015)	[17]	China	Journal Paper - Journal of Energy Policy	Management Systems
18	Ding C, et al. (2015)	[18]	Taiwan	Journal Paper - Safety Science	Applied Safety Management
19	Saqib N., Siddiqi M. (2016)	[19]	Pakistan	Journal Paper - Safety Science	Applied Safety Management

20	N. Dechy et al. (2016)	[20]	France	Conference Paper - International Conference on Human and Organizational Aspects of Assuring Nuclear Safety	Frameworks and Theories for Safety Management
21	Vieira Neto S., et al. (2017)	[21]	Brasil	Conference Paper - International Nuclear Atlantic Conference	Applied Safety Management
22	López de Castro, et al. (2017)	[22]	Spain	Journal Paper - Journal of Accident Analysis and Prevention	Safety Culture
23	International Nuclear Safety Advisor Group (2017)	[23]	Austria	Professional Report	Frameworks and Theories for Safety Management
24	Kim J., et al. (2018)	[24]	South Korea	Journal Paper - Annals of Nuclear Energy	Applied Safety Management
25	Martínez-Córcoles M., et al. (2018)	[25]	Spain	Journal Paper - Journal of Psychologist papers.	Applied Safety Management
26	Wahlström B. (2018)	[26]	Finland	Journal Paper - Safety Science	Frameworks and Theories for Safety Management
27	Sui Y. et al. (2018)	[27]	China	Journal Paper – Journal of Cleaner Production	Management Systems

3.1 Quantitative distribution of the articles.

The thematic distribution of the articles is detailed in Table 2. In this table, it can be seen that the dominant thematic areas are “Frameworks and Theories for Safety Management” with ten papers, followed by “Applied Safety Management” with seven documents, and finally with five papers “Safety Culture” and also 5 for “Management Systems”. Regarding the distribution of the types of documents retrieved, most are concentrated on papers published in Journals with 14 papers, followed by conference papers with ten papers and finally in Professional Reports with three documents.

The journals with the most publications are Safety Science (5 papers) and Journal of Risk Analysis (2 papers), the rest of the publications (7 papers) have each been made in other Journals (Journal of Risk Analysis, of Safety Research, of Energy Policy, of Accident Analysis and Prevention, of Nuclear Energy, of Psychologist papers, of Cleaner Production). This seems to confirm the multidisciplinary nature of SM.

Regarding the Conference Papers, they do not focus on any particular topic. These being presented at different conferences: of Human Factors and Ergonomics Society Annual Meeting, of Institution of Chemical Engineers Symposium Series, of IEEE IEEM, of International Conference on Operational Safety Experience and Performance of NPPs and Fuel Cycle Facilities, of World congress on Ergonomics - Designing a sustainable future, of Probabilistic Safety Assessment and Management, of International Conference on Automatic Control and Artificial Intelligence, of Conference on Safety and Reliability of Complex Engineering Systems, of International Conference on Human and Organizational Aspects of Assuring Nuclear Safety and of International Nuclear Atlantic Conference. The professional reports 2 correspond to INSAG and 1 to SAE International.

Table 2 Thematic Distribution and Tipology of Recovered Documents

Quantitative Distribution by Thematic Area		Quantitative Distribution by Type of Document		
Thematic Area	**Total Quantity (percentage)**	**Journal Papers (percentage)**	**Conference Papers (percentage)**	**Professional Reports (percentage)**
Frameworks and Theories for Safety Management	10 (37%)	6 (32%)	2 (40%)	2 (67%)
Applied Safety Management	7 (26%)	6 (32%)	1 (20%)	0 (0%)
Safety Culture	5 (19%)	5 (26%)	0 (0%)	0 (0%)
Management Systems	5 (19%)	2 (11%)	2 (40%)	1 (33%)
Total	**27 (100%)**	**19 (100%)**	**5 (100%)**	**3 (100%)**

The temporal distribution of the documents seems to be homogeneous, and there are contributions in all thematic areas. The authors with the largest number of papers carried out or in which they had participation as the main author are Wahlström B. with a total of 3 papers (2010, 2014 and 2018) and as the second author, also with three papers to Rollenhagen C. (2010, 2012 and 2014). Finally, with two documents, *INSAG* contributed in 2010, 2017. All contribute to the theoretical field (thematic area "Frameworks or Theories of Safety Management").

The years where most papers were found were in 2009, 2012, 2015, and 2018 with four papers. For 2009 Zhai Z.; Cullen R.; Kavoulinas et al.; Hildebrand M. et al. For 2012 the papers corresponding to Reiman T. & Rollenghagen C.; Himanen R. et al.; Shan Z. and Wu Y., et al., The 2015 papers are by Kouabenan D. et al.; Akselsson R.; Ruimin Mu et al. and Ding C., et al. Finally in 2018 the works found were by the following authors, Wahlström B; Sui Y. et al.; Kim J. et al. and de Martínez-Córcoles M., et al.

The largest amount of contributions come from China with five documents, followed by Sweden with three documents. There are two documents with affiliations in Austria, Finland, Spain, the Netherlands, and France. Finally, with 1 document, they make contributions: Norway, South Korea, Mexico, Taiwan, USA, Brazil, Canada, Pakistan, and the UK.

The number of publications in China is explained by the boom and development that nuclear energy has had in that country during the last twenty years.

3.2 Content Analysis.

This section presents a brief synthesis and discussion of the recovered documents, classified in the different thematic areas. It begins with the thematic area of "Frameworks and Theories for Safety Management," in which the documents present the greatest conceptual development. From this area, it would be expected that the other areas would come off. It will continue with the thematic area of "Applied Safety Management", followed by "Safety Culture" and it will end with "Management Systems".

The research discussion goes from the more general to the more specific contributions. Also, this development will be crossed with the contribution of the main theories of safety thinking that were detailed in section 1 of the introduction.

Frameworks and Theories for Safety Management.

Wahslström & Rollenhagen (2010) in their paper "Models, Methods and tools for Safety Management" indicates that there is no integrative model that can be used to understand or describe SM without falling into a trivial representation that is useless for plant managers or reactors heads, decision-makers or senior management of a reactor operating organization. Furthermore, these authors raise the need to develop a framework or a framework model that can integrate the contributions of all or methods that explain, analyze, or describe some relevant factor in safety. This need becomes stronger when the question is asked, "What is safe enough?" because these authors still have no answer.

These same authors in 2014, take up the analysis, in their previous work, and the paper "Safety Management as a multi-level control problem". They propose to use a controlling metaphor to understand the problem of integrated and operational nuclear safety. This metaphor is useful for the design stages and their evaluation and should be adopted in the reactors' operation stage. This paper identifies the multiplicity of hierarchical levels involved in reactor safety. This multiplicity of levels and actors requires using a common language for a common understanding of the problem. For this, the metaphor of control is useful to define a conceptual framework for the identification, definition, and eventual integration of various models, also, for their input and output variables and state spaces. Finally, the authors propose to use the polycentric control design tools and the Man, Technology, Organization and Information model (MTOI) to integrate these conditioning factors of nuclear SM.

The paper "Systemic Thinking in support of SM in nuclear power plants" by Wahlström (2018), considers in the definition of the theoretical proposal of the works of Wahslström & Rollenhagen from 2010 and 2018. This authors defining a model of a Socio-technical system that can be used. The reality of an operational NPP presents dynamic interactions between the design of the operation and the practices of the operation. Each of them is feedback to the other two. For this reason, a system of systems models is required. This mode must consider the model plant states and perform an integration between hard and soft operating systems. This integration in Wahlström's words is only possible from the qualitative-quantitative systems of systems thinking "I see systemic thinking as a broad concept involving various kinds of models as well as the need for considering both entireties and details".

The Technological view of the problem, and in particular in the design stage, deals with the plant architecture from the System Breakdown Structure (SBS). In the nuclear industry, SBS is known as structures, systems, and components (SSC). And tools and techniques of safety engineering are applied to it. These results guide SM during operation.

Related to the human-related view, the design of the prevention issues is aboard from the Hazards and Consequences analysis. This analysis identifies the natural, technical, or human sources and their relationship with the different plant states. Then again, Safety engineering encompasses actions for eliminating, isolating, controlling, and mitigating these identified risks applying mainly the concept of Defense in Depth (INSAG, 1996). In that to address the model of Failures, errors and deficiencies (risk analysis) from human errors and organizational deficiencies are still difficult. In this sense, it is

convenient to consider the drivers and goals of the operating organization, the management systems involved, and the use of tools for decision support. Also, for other organizational issues, the methods of selection, education, training of personnel, the managers and leaders' behavior, and the involvement of the Stakeholders in the safety process are important. Considering this, the MTOI model seems the better way to accomplish it.

As a contribution to this vision, INSAG makes two clarifying contributions. The first, in 2011, the document "A Framework for an Integrated Risk-Informed Decision Making Process," details a methodology for the integration of operational risk from probabilistic (technology and human-related) and deterministic (technology-related) analysis. This methodology proposes a way of integrating the different approaches of the classical safety assessment. This is done by establishing requirements that focus attention on the reactor operating license holder and how to ensure that a decision made in one area does not conflict with other decisions. This proposal does not contemplate a multi-level vision in the decision-making characteristic of the operational face. Furthermore, it seems to have greater applicability to design tasks than to operational management tasks.

Meanwhile, INSAG in his document “Ensuring Robust National Nuclear Safety Systems - Institutional Strength in Depth” in 2017, he proposed a way to integrate this process and online safety analysis by merging the concept of defense in depth traditionally applied to the technological dimension of SM. This proposal considers the institutional dimension of risk and its impact at the operational level. This aspect is directly related to the lessons learned in the Fukushima accident. Likewise, with a pragmatic perspective, he presents the systemic vision proposed by Rasmussen (1997) as his main influence. In this pragmatic vision, the role of the regulatory entity and its deficiencies as an influencing factor in safety are included in the safety analysis. It also raises the need for a systemic vision of the SM problem that integrates human, organizational, and technical factors. The way to approach a Robust Nuclear Safety System as supra operational level is considering three levels. These levels are the level of the operator and holder of the operating license and its environment, the level of the regulatory body and the level of the stakeholders, and the exercise of their pressures.

Dechy et al. (2016) present a paper addressing modes of transfer of the lessons learned in industrial accidents to the nuclear industry. They were starting to wonder if all majors’ accidents have socio-technical roots (beyond technological differences). The authors identify common patterns and causes between both industries and propose two types of transfer the content issue: (a)“Knowledge of Accidents” and (b)“Culture of Accidents”. From them, and a bibliographic review identifies the so-called pathogenic organizational factors.

Finally, in this thematic area, the papers by Zhai et al. (2009) present the Event Analysis and Report System (for incidents or accidents) from 3 conceptual levels (root, nature, and surface). It states that an event is produced by socio-technical causes and a variety of factors (technical, human, and organizational) that must be integrated. This model takes some hypotheses from Reason (1997) since it proposes that: "While technical factors can be random, human and organizational factors do not appear randomly

but interact with each other through a hierarchical structure of three levels: behavior (what), contextual (where) and conceptual (how)".

The authors propose using Failure Modes and Effects Analysis (FMEA) and Probabilistic Safety Analysis (PSA) to solve the qualitative dimensions of the problem. And for the quantitative analysis, proposes to use Bayesian Belief Net (BBF), and deterministic dynamic techniques. For them, it recognizes that the greatest source of inter-certainties comes from human and organizational factors. These should be analyzed in the framework of causal analyzes based on plant operational experience. This proposal seems to consider a complete image of a relevant event for the reactor's SM. But it is a tool for analyzing causes and not postulates proactive concepts that anticipate unwanted events.

Viera-Nieto et al. (2017), in their work Soft Systems Methodology as a Systemic Approach to Nuclear SM, explores the applicability of soft systems theory to SM issues. In their work, they emphasize that this methodology is useful for modeling complex socio-technical systems. Carry out a bibliographic review and establish the necessary analyzes in this method. The analyzes are that of roles (individuals), social (cultural), and political. To these analyzes is added the description of the vision of the problem of each stakeholder. Then activity models are made from identifying the clients, actors, transformation, "Weltanschauung", Owners, and Environmental constraints. Finally, highlights the experience of applying these systems in the Brazilian nuclear system.

In 2012, Wu et al. (2012) proposed the affecting factors of SM of nuclear power based on the Interpretive Structural Modeling (ISM) methodology. This tool is used for represented relationships with a multi-level hierarchical structure visually. The results is a very conceptual model with relations between safety factors that are more compatible with applying to design SM than operational SM. It is expected not to differentiate the stages of the life cycle of a reactor. The focus on safety should be consistent between stages. If the design stage were considered as the genesis of the modeling, it would be more applicable than considering the reactor's operational actions. Therefore, the work recommends refining and expanding the model using other tools such as Fuzzy AHP.

Applied Safety Management.

In this thematic area, papers were recovered with contributions in two directions. The first is about the measurement of safety performance (Hildebrandt et al. 2009), (Himanen et al. 2012), (Saquib et al. 2016), and (Martinez-Córcoles et al. 2018). The second concerning the development of tools to measure levels or degrees of SM (Ding et al. 2015), (Paradies, 2011) and (Kim et al. 2018).

As mentioned, several authors discuss the measurement of safety and performance. Saquib et al. (2016) reflect on the consistency of the use of various safety performance indicators. This consistency is questionable when these indicators are measured to calculate a single comprehensive and strategic indicator. Within the framework of this strategic safety indicator, the weighting of these different operational indicators has different impacts. That impact depends on the independence of the input data and how

those data are independent of each other when they affect multiple indicators. To inhibit these unwanted effects, he proposes an objective equation.

Meanwhile, Martínez-Córcoles et al. (2018) state that the literature on safety behavior is scarce. Similarly, the definition of safety performance should be narrowed. To this end, it carries out a bibliographic review focused on measuring human factor safety in the nuclear industry context. He highlights his observation on safety compliance in terms of how prescriptive regulation appears to be in this industry. He attributes this to potential hazard by the understand of safety performance through relating risk, safety engagement, and safety compliance.

Hildebrandt et al. (2009) et al., discuss the need to modernize the Human Reliability Assessment (HRA) in the context of SM. For this purpose, the use and formation of communities of practice are proposed. From this, they propose a "living" HRA that takes as input the results of these communities of practice. Recognize the value of HRA as part of the Probabilistic Safety Analysis (PRA) of a nuclear power plant. It also identifies the need to develop methods that contemplate the cognitive dimensions of the operators.

Himanen et al. (2012) describe the regulatory requirements of the nuclear industry in Finland. This was done for four operational nuclear power plants. Describe how the PRA development process contributes to SM practices in the prevention of severe accidents. This is due to the need to define probabilistic safety criteria. This includes the frequency of core damage, a risk metric in nuclear safety. As the three levels for PRA was applied, the Finnish NPP operating institution gained mastery over these and other risk-informed applications.

Paradies (2011) qualitatively, compares the results of military nuclear reactors used for propulsion with reactors operated by civil organizations used to electricity generation. Given the exceptional safety record of the United States Navy reactor process, the author wonders how much this influences the military safety process. To answer this question, compare the philosophy of the US Navy with the process SM of the Chemical Process Center and its safety guidelines. In his analysis, the author identifies that there are many gaps between them. The gaps are identified in the difference in rigor posed by the military management model compared to the civilian one. That rigor seems to contribute to better safety results.

Ding (2015) develops a model to identify hidden factors and risk determinants in the nuclear power plant's operation. To do this, he analyzes the failure records of 342 pumps from a large nuclear power plant with a period of 28 years. To do this, use the Latent Growth Modeling (LGM) method. The author postulates hypotheses based on a bibliographic review and the characteristics of the expected failures of the different types of pumps. Using the mathematical model, he confirms four of his five hypotheses. Their contribution seems to be that identifying the factors contributing to risk in SM is always an unfinished task due to hidden factors.

Kim (2018), in his article "Development of a quantitative resilience model for nuclear power plants", is the first author to present the results of the application of the theoretical proposals of Hollnagel et al. (2006). This proposed model takes as input the lessons learned from Fukushima and the French electricity company's experience. To do this, resistance is defined based on the relationship of performance variables such as

Anticipation, Adaptation, Collective Functioning, and Robustness. To develop the quantitative model, 222 event reports from 2003 to 2016 are used. Finally, validate your model through statistical analysis, with data from 26 nuclear power plants. They argue that this model is complementary to classical nuclear safety analyzes results, both probabilistic and deterministic.Given the recent nature of this model, it is convenient to apply and validate it in other nuclear power plants in countries with cultures other than Korean.

Safety Culture.

In this thematic area, papers were recovered with contributions in 2 directions. The first concerning the discussion and utility of the concept of Safety Culture (Guldemund, 2010) and (Cullen, 2009). The second with the measurement of the safety climate as a proxy for the Culture of Safety of the organization (Latorre Navarro et al. 2013), (Kouabenan, et al. 2015), and (López de Castro et al. 2017).

Guldemun (2010), in his article "(Mis) understanding Safety Culture and Its Relationship to Safety Management," criticizes the treatment that academics and practitioners have given to the concept of Safety Culture (SC). His strongest statement is that "the culture concept is deprived of much of its depth and subtlety, and is morphed into a grab bag of behavioral and other visible characteristics, without reference to the meaning these characteristics might have and often infused with normative overtones."

In this sense, he performs a bibliographic review comparing SC's concept according to the components and layers that each author postulates. To link the SC to SM, he inspects how the SC assessment contributes to nuclear safety assessments,

The treatment of SC as the main basis for the study of nuclear safety is addressed by Cullen (2009). In his paper, he presents a practical way of internalizing the concept of the safety processes of a plant. When presenting the description of perception in the different processes, the differences in the vision of the participants in each one are shown. It concludes on the need to take actions to achieve a common understanding of SC's implications in all processes.

Another aspect of the academic application that was revealed about SC is its application to understand and measure the safety climate of the nuclear reactor's operating organization. In this sense, Latorre Navarro et al. (2013) present the development of a questionnaire and a standardized scale to be able to understand the nuclear safety climate in an NPP in Spain. He correlated these concepts with formal safety practices such as written procedures, and observable variables such as safety behavior and time pressure. Finally, he validates its results using factor analysis.

Koabenan et al. in 2015 argue that the safety climate is the key variable to explain the perceived risk and the involvement in safety on the part of the front-line managers of 2 French NPPs. To do this, it conducts questionnaires in the field to 63 managers. Their results are analyzed by SSPS software using Chronbach's Alpha test. The hypothesis is confirmed by its results. As a particular observation, they find that employees' safety behavior has almost no influence from managers. While the direct supervisors of the activities are influential in the perception of safety, in this sense, the paper by Castro et al. (2017) presents a similar work, carrying out a comparative study on the perception of daily safety by applying a Safety Culture Enactment Questionnaire to the staff of

two Spanish NPPs. They use Confirmatory Factor Analysis to validate the consistency of the results and conclude that it is a valid tool for measuring safety culture.

Management Systems.

Papers with contributions in 2 directions were recovered in this thematic area. The first concern is conceptual discussions on applications of management systems Kavouliunas, et al. (2009) and Akselsson (2015). The second, with the implementation of management systems for safety in China Shan (2012), Ruimin, et al. (2015), Sui (2018).

For the discussion of the management systems' applications, Akselson (2015) recognizes that the requirements for these systems are relatively new and are in development. It also recognizes that there are no mature systems in the industry, particularly in NPPs. It still takes a lot of effort to have cadres of highly trained managers in the new vision of SM applied trough a management system.

On the other hand, it addresses the discussion about the indicators. It is necessary to propose indicators that can capture subtle and little obvious behaviors, deviations, or events that initiate accidents. Meanwhile, Kavouliunas (2009) establishes that nuclear SMS require developing a structured risk management process. The risks come not only from technological failures but from the interaction of technology with the man. This author recommends as imperative to develop objective decision-making mechanisms based on NPP data and risk. For this, developments must be made that integrate the probabilistic, deterministic, and quantifiable elements.

For experience in the implementation of management systems for safety in China, Ruimin (2015), in his paper "China's approach to nuclear safety - From the perspective of policy and institutional system," details the country's nuclear safety policy. This is reinforced because mechanisms that prioritize it are established from the political and institutional perspectives. Laws, institutions, ministries, and organizations aligned on a single priority. In this work, all the interventions of these elements are mapped during the life cycle of the numerous NPPs that are operational and under development.

Shan (2012) presents the experiences gained by the China General Nuclear Program Group based on the proposals of the National Regulatory Commission of the USA. To do this, they developed a Reactor Supervision Process. A system independent of the classic already implemented. This new system considers an implementation based on risk management and structured on three levels: the unit level, the site level, and the multi-site level.

Finally, Sui (2018) details the experience gained in implementing a SMS in an NPP in eastern China. This implementation was leveraged by the development of a computer system that made it possible to standardize data processing for decision-making.

4 Discussion and Future Research.

After the Fukushima Daichii accident, there is agreement on the risk factors and causes of nuclear accidents. These factors are technological, human, organizational, and institutional (which includes the regulatory). On the other hand, the models revealed in this paper for the thematic area of Frameworks and theories of SM still cover

spaces that are too abstract and somewhat distant from those of technological safety engineering. No postulates are observed that relate physical variables of the plant and the "soft" variables of safety. In this sense, the concept of Safety Culture (a strong and useful concept) seems to become a free interpretation of each author that is diffuse or lax.

It is observed that these approaches require a complex process of internalization within each organization, and it would be advisable to review their scope and definition ontologically. On the other hand, as it is a discipline proclaimed as multidisciplinary, the application of tools from the theoretical field of SM to the practical field is wide but much unconnected in its results and many other times inconclusive. There is a research opportunity in addressing the question of what and how much is safe for the nuclear industry.

Regarding the recovered documents, 27 documents relevant to NPP were obtained, but none for nuclear research reactors. Although there was an accident in this type of reactor (RA-2, 1982) and there are currently more than 100 such reactors in operation, this object of study does not seem to arouse interest in the academy. Perhaps it is because both the risks, magnitudes, objectives, and interests are quite different for NPP and RR. Regarding the academic treatment revealed on SMS applied to the nuclear industry, there is no evidence of common features among them (framework, architecture, principles). In this sense, there is a theoretical gap in the consolidation of a specialized methodological framework that contemplates the treatment of the risk inherent in this industry.

As Wahlström (2010) stated, it is necessary to propose a framework that allows integrating all the models, meta-models, and concepts that were presented. For this, the proposal of Wahlström & Rollenhagen (2014) about assuming the metacentric of polycentric control and INSAG (2017) and Wahlström (2018) of implementing the systems system vision and the MTOI model seem to be the most appropriate to integrate them. Likewise, this proposal would allow a priori to be able to use as inputs the results of mature nuclear safety engineering tools in the nuclear industry and High Reliable Organizations.

5 Conclusions

SM was contextualized in the history of safety thinking and the causes of nuclear accidents and major industrial accidents.

The state of the art of SM for nuclear reactors was systematically surveyed. Science Direct, Scopus, and INIS were used to this end, and 27 academic articles and professional reports were retrieved. From this, the actual academic scope of nuclear SM has been identified. According to the methodology proposed by Olivera et al. (2019). Finally, the findings were critically discussed, and new lines of research were recommended.

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Planejamento de Vendas e Operações e Planejamento Integrado de Negócios em um Banco Privado do Brasil

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Resumo. Quando se pensa em diferencial estratégico para melhorar a competitividade de um negócio, quase sempre os processos de S&OP (*Sales and Operations Planning*) e sua evolução, o IBP (*Integrated Business Planning*), estão em pauta. Estes processos, descrevem como os negócios devem criar e integrar seus planos estratégicos (vendas, marketing, desenvolvimento, fabricação, logística e finanças) para gerenciar o negócio e ao mesmo tempo, equilibrar o que está sendo produzido com que está sendo vendido. Este artigo apresenta uma pesquisa sobre como os processos de S&OP e IBP podem melhorar o fluxo de trabalho em um banco privado do Brasil, bem como podem ser usados em empresas ou departamentos do setor de serviços, e não só em empresas do setor industrial, setor precursor onde o S&OP foi utilizado pela primeira vez. O método de pesquisa adotado foi o de pesquisa-ação tendo sido realizada uma coleta de dados de departamentos específicos do banco privado e, até o momento, foram sugeridas algumas mudanças nos fluxos de trabalho. Na próxima etapa deste trabalho, será utilizado um modelo de maturidade de S&OP/IBP, com intuito de identificar novas oportunidades de melhoria nos processos do banco privado e medir os resultados destas melhorias.

Palavras-chave: Banco, Planejamento Integrado de Negócios, Planejamento de Vendas e Operações, Serviço.

1 Introdução

Num mercado cada vez mais concorrido, o alinhamento dos processos com os objetivos estratégicos da empresa é requisito mínimo para atingimento do sucesso nas empresas quando se pensa no longo prazo [1].

Cada área funcional de uma organização tende a influenciar os processos de modo a atingir os objetivos e resultados que lhes são atribuídos como meta. Quando ocorre um desalinhamento das métricas para avaliação do resultado entre as funções, é natural que haja uma intensificação dos conflitos. Por exemplo, se a meta da área de vendas é o

faturamento, é natural que a previsão de vendas seja superestimada para garantir a disponibilidade de produtos.

Dados os interesses divergentes, a importância da colaboração e a integração na tomada de decisão entre as áreas funcionais, a introdução do S&OP (*Sales and Operations Planning*) ou Planejamento de Vendas e Operações, nas empresas é de grande valia, na medida em que a finalidade deste processo é justamente desdobrar o plano estratégico da empresa em planos táticos integrados para as diferentes áreas [2].

As empresas que têm os processos de S&OP implantados em seus fluxos de trabalho em relação as empresas que não têm, apresentam os resultados mostrados na Fig. 1.

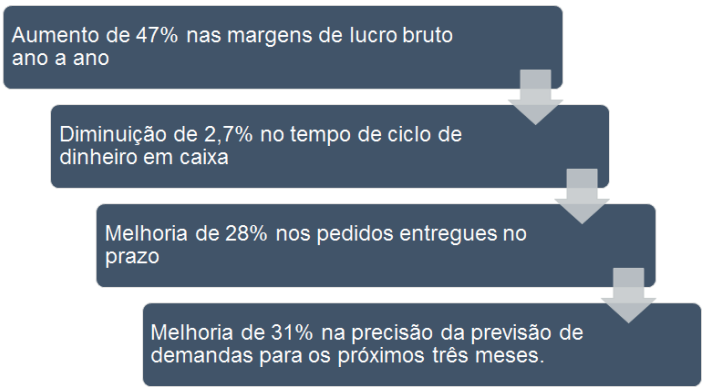

Fig. 1. Benefícios da implantação do S&OP nas empresas. Fonte: [3].

Os benefícios dos processos de S&OP podem reduzir de forma significativa os custos, aumentar a agilidade, melhorar o relacionamento com cliente e aumentar os lucros das empresas A sistemática preconizada pelo S&OP envolve três abordagens distintos tais como planejamento executivo, planejamento tático e planejamento estratégico [3].

A etapa de planejamento estratégico também recebe a denominação de IBP (*Integrated Business Planning*) ou Planejamento Integrado de Negócios. Porém, há quem defenda que o IBP abrange também as atividades do planejamento executivo e tático em sua finalidade [3]. Cenários hipotéticos podem ser criados para simular projeções financeiras, planejar futuros investimentos e até mesmo, comparar possíveis estratégias de atuação por meio de métricas volumétricas e financeiras.

Analisando-se o IBP, sua principal finalidade é garantir o alinhamento contínuo entre os planos de demanda, estoque, suprimento e fabricação, maximizar o desempenho operacional e atender os objetivos financeiros. O IBP é uma nova arma de competição para os responsáveis pela cadeia de suprimentos das empresas na batalha para direcionar e maximizar as decisões de negócios para o planejamento de curto e longo prazo. O IBP pode abranger todos os horizontes de tempo dentro do S&OP.

Neste contexto, o principal objetivo neste artigo foi avaliar e propor a implantação do IBP no fluxo de trabalho atual dos departamentos específicos de um banco privado

brasileiro, seguindo o procedimento previamente estabelecido pelos processos de S&OP.

O artigo está organizado da seguinte forma: na Seção 2 apresenta-se a revisão da literatura, focada nos conceitos de S&OP e IBP. A Seção 3 faz referência ao método de pesquisa. Na Seção 4 apresenta-se proposta de implantação do IBP. Finalmente na Sessão 5 estão as conclusões parciais do trabalho, bem como as próximas etapas a serem realizadas, sendo seguidas pelas referências bibliográficas utilizadas neste texto.

2 Revisão da Literatura

2.1 Sales and Operations Planning

S&OP é um processo para desenvolver planos táticos que forneçam à administração, a capacidade de direcionar estrategicamente seus negócios para obter vantagem competitiva no mercado. O S&OP integra todos os planos de negócios (vendas, marketing, desenvolvimento, fabricação, logística e financeiro) para criar uma cadeia de suprimentos otimizada com foco no atendimento ao cliente [4].

Cada membro da equipe multifuncional, se reúne rotineiramente para planejar e trazer para o processo de S&OP, uma perspectiva específica durante o desenvolvimento dos planos ou previsões de oferta e demanda [5].

S&OP é realizado pelo menos uma vez por mês e é revisado pela administração em um nível agregado (família de produtos). O processo deve conciliar todos os planos de oferta, demanda e novos produtos nos níveis de detalhe e agregado. Depois, vincular-se ao plano de negócios. É a declaração definitiva dos planos da empresa para o curto e médio prazo, cobrindo um horizonte suficiente para planejar recursos e apoiar o processo anual de planejamento de negócios [4].

S&OP é basicamente uma combinação de um plano mestre de produção com um planejamento de demanda. Tradicionalmente, o volume de demanda é determinado em primeiro lugar e depois, incluído no plano mestre de produção. Também é possível incluir KPIs financeiros com informações adicionais e executar análises hipotéticas para identificar alternativas de plano que produzam uma melhoria geral [6].

S&OP foi criado no final dos anos 1980 por Dick Ling e tinha como foco principal fazer o MRP II (*Manufacturing Resource Planning*) funcionar em uma única fábrica de uma empresa. Na época, o S&OP era considerado como um avanço, porque muitas empresas apresentam seus planos anuais, planos de vendas e planos de produção apartados. Existiam muitos erros nas projeções e informações desalinhadas entre os departamentos das empresas. O departamento de Finanças atuava frequentemente como arbitro entre as disputas entre os departamentos de vendas, marketing e produção [7].

A premissa do S&OP tradicional é que o atendimento ao cliente e o inventário é o "resultado final". Para gerenciar o processo, precisamos gerenciar os drivers, ou seja, demanda e fornecimento. S&OP foi um avanço para época, pois obrigou os departamentos de Vendas, Marketing e Produção, a alinharem uma vez por mês, qual seria o número de produtos a serem vendidos, produzidos e armazenados [7].

2.2 Integrated Business Planning

IBP é um modelo de melhores práticas que amplia os princípios do S&OP para um gerenciamento contínuo de processos. Ele fornece, aos tomadores de decisão da empresa, os planos estratégicos alinhados para facilitarem a decisão de como alocar os recursos críticos para satisfazer o cliente e consequentemente, aumentar a lucratividade do negócio [8]. O IBP oferece várias vantagens e benefícios competitivos para empresa, e ilustrado na Fig. 2.

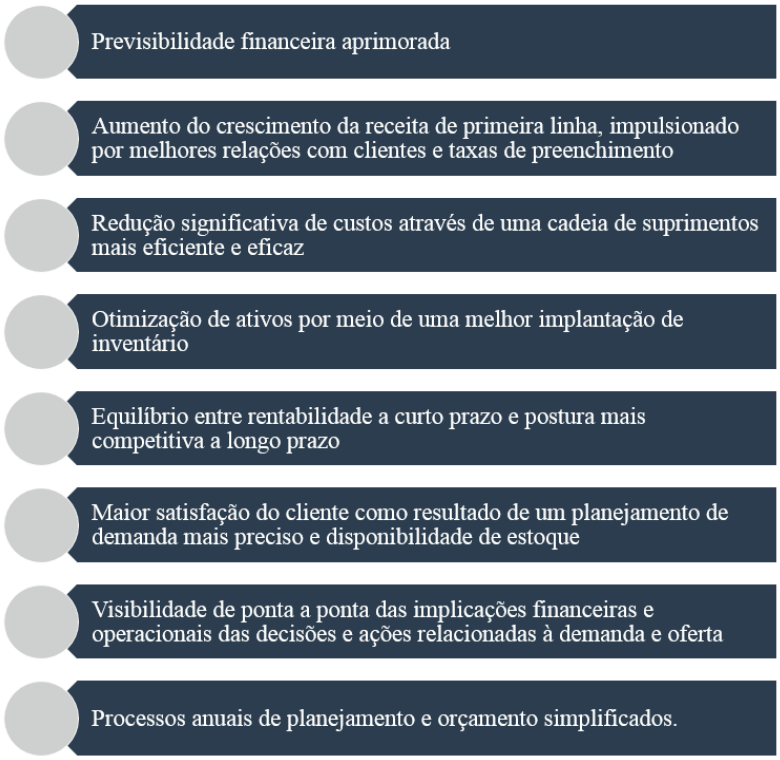

Fig. 2. Benefícios proporcionados pelo IBP implantado. Fonte: [8].

2.3 Desafios para implementação do IBP

Os principais desafios na implantação do IBP são mensurar de forma eficaz o que é necessário para o processo, bem como identificar como os recursos humanos e o gerenciamento de relacionamentos podem impactar os projetos. Para que o IBP seja implantado com sucesso, existem cinco fatores que os executivos precisam focar no processo de implantação [8]:

Comprometimento inabalável dos responsáveis pelos processos na implantação do IBP: Os executivos ou responsáveis pelos processos, devem abraçar a mudança em

primeiro lugar e depois mostrar seu comprometimento inabalável com o novo processo para todas as áreas envolvidas. Reuniões breves e individuais com todos os envolvidos pelos processos, podem ajudar a verificar sua adesão à iniciativa do IBP e alinhar seus papeis no novo fluxo.

Aproveitar tecnologias que se integrem com IBP: Uma estratégia primordial é incluir nos processos de IBP, as melhores soluções tecnológicas disponíveis no mercado. Com automação dos processos de coleta de dados, revisão de dados e divulgação de dados, isso libera recursos para análise de maiores valores. A tecnologia pode ser usada também para gerenciar prazos e fluxos de trabalho, unificar modelos de dados e integrar diferentes sistemas, e ainda, oferecer recursos avançados de planejamento e análises. Por fim, podem ser gerados de forma rápida, automática e tempo real, simulações hipotéticas de cenários que impactem a lucratividade, capacidade de produção, tempo de entrega, nível de serviço e desempenho de novos fornecedores.

Ter o argumento de mudança de processos bem definido: É crucial que os argumentos para mudança estejam bem definidos para garantir o alinhamento entre todos os envolvidos pelo processo. O sucesso depende do desenvolvimento de uma necessidade convincente de mudança com base na situação atual da empresa e nas oportunidades de mercado. Metas e objetivos do IBP precisam ser claramente articulados e definidos. O projeto deve quantificar os resultados operacionais e financeiros esperados, e identificar métricas que serão usadas para mostrar o progresso. Estabelecer um verdadeiro processo de IBP orientado por métricas é a base para maximizar a eficiência e a agilidade de qualquer organização.

Empregar procedimento comprovado para implantação do IBP: Ter um procedimento estruturado e comprovado para liderar a jornada de transformação também é crucial. Um plano formal para implementar o processo de IBP - começando com a equipe de transformação e depois envolvendo os principais interessados e líderes - deve ser desenvolvido em primeiro lugar e executado de forma eficaz à medida que as mudanças passam pelas áreas envolvidas. O plano deve ser amplo o suficiente para cobrir o planejamento, a implementação e a manutenção das mudanças. Um procedimento estruturado exige uma coleta e análise de dados rápida e eficiente, e um redesenho das estratégias, dos processos e sistemas impactados pela mudança.

Ter uma governança eficaz e manter um alto nível de energia: Ter as pessoas certas nos processos de governança de ideias, é tão importante quanto ter os processos corretos. Isso inclui a incorporação de membros de finanças, engenharia, cadeia de suprimentos, vendas, planejamento de demanda e planejamento de suprimentos, entre outros, com o conhecimento e as habilidades necessárias para gerenciar o processo de transformação do IBP. A governança deve ajudar a estabelecer controles eficientes, transparentes e livres de influências, participar de forma regular nas reuniões e apoiar as decisões tomadas como parte do processo do IBP. As partes interessadas precisam saber por que as mudanças estão acontecendo, como o trabalho delas se transformará, o que se espera delas durante e após o programa de transformação, como serão avaliadas e quais benefícios o sucesso trará para elas pessoalmente.

2.4 Modelo de Maturidade

Para avaliar o grau de maturidade que o negócio/departamento está no momento, a consultoria Oliver Wight, desenvolveu um modelo de maturidade onde ela divide o negócio em duas fases e cinco níveis de avaliação. A fase 1, demonstra se os processos de S&OP estão implantados no negócio/departamento e se existe capacidade para migração para o IBP. Na fase 2, o IBP está implementado no negócio/departamento [9]:

Fase 1, nível 1: Os processos de gerenciamento são desconectados. As reuniões são realizadas de forma tradicional e focadas nos assuntos que já ocorreram. O processo orçamentário anual não tem todos as informações necessárias para que as projeções futuras sejam feitas adequadamente. O negócio não apresenta objetivos e medidas em quantidades adequadas para seu gerenciamento, e ainda, as informações podem estar desalinhadas. Os indivíduos responsáveis pelos processos apresentam uma postura mais defensiva em relação a seus resultados.

Fase 1, nível 2: Os fundamentos do S&OP são aplicados parcialmente. Todas as ações têm seus responsáveis definido, métricas para serem medidas e estruturas definidas. O foco das ações é equilibrar de forma tática a demanda e a oferta. São criados indicadores para gerenciar a cadeia de suprimentos. O comportamento da equipe é voltado para o desafio, mas o trabalho em equipe quase não ocorre.

Fase1, nível 3: S&OP está implementado. O planejamento operacional e financeiro está integrado. Os indicadores operacionais estão implantados e aumentam a eficácia operacional, permitindo uma capacidade de 95% de entrega do processo. Os problemas são identificados e geram informações que subsidiam as tomadas de decisão para sua resolução. Os números do orçamento são substituídos pelos números gerados pelo S&OP. O trabalho de equipe é demonstrado durante todo o processo.

Fase 2, nível 4: IBP está implementado. O processo é continuo do gerenciamento de negócios. As estratégias são confrontadas com seus problemas e o foco é total em prioridades que tornam o negócio mais competitivo. O negócio ou departamento são constantemente analisados com intuito de gerar prioridades de melhoria e ações que corrijam os problemas encontrados. Os processos são remodelados frequentemente para atender as mudanças na estrutura organizacional, e utilizados para implantar e direcionar a proposta de valor.

Fase 2, nível 5: IBP está em um nível alto de maturidade. Todos os processos são impulsionados para otimização responsiva do negócio em busca de estratégias para melhorar o negócio. O gerenciamento de problemas e planejamento de cenários alternativos é constante para todo o negócio

2.5 Serviço de Atendimento ao Cliente

A caracterização do que seja um serviço, de forma clara e indiscutível, é muito difícil. Os autores que têm estudado o assunto muitas vezes definem o que não é serviço para, a partir daí, conceituá-lo [1].

Vê-se, pois, que na operação em serviços é necessário o encontro entre o fornecedor e o cliente. O local no qual acontece este encontro é denominado front office. O cliente recebe o serviço, o fornecedor fica frente a frente com o cliente, e todo tipo de variabilidade e novas situações podem ocorrer; enfim, onde o controle é muito difícil.

Na prestação de serviço, a presença do cliente é parte do processo. Dependendo da natureza, como reparo em um eletrodoméstico, o serviço será executado em outro local – oficina, por exemplo -, não na presença do cliente. Este local é denominado *back room* ou *back office*, cuja características são de baixo contato com o cliente, maior previsibilidade, possibilidade de padronização e melhor controle.

Ao longo de todo o desenvolvimento dos processos de fabricação de bens tangíveis, estiveram presentes, sempre de forma crescente, os serviços. Pode-se afirmar que, até meados da década de 1950, a indústria de transformação era a que mais se destacava no cenário político e econômico mundial, mas atualmente, isto não é mais verdadeiro [1].

Analisando-se a Fig. 3, tem-se a exata noção que a importância relativa da indústria no PIB (Produto Interno Bruto) nacional vem diminuindo ao longo do tempo e o setor de serviços tem crescido em relevância no Brasil [10].

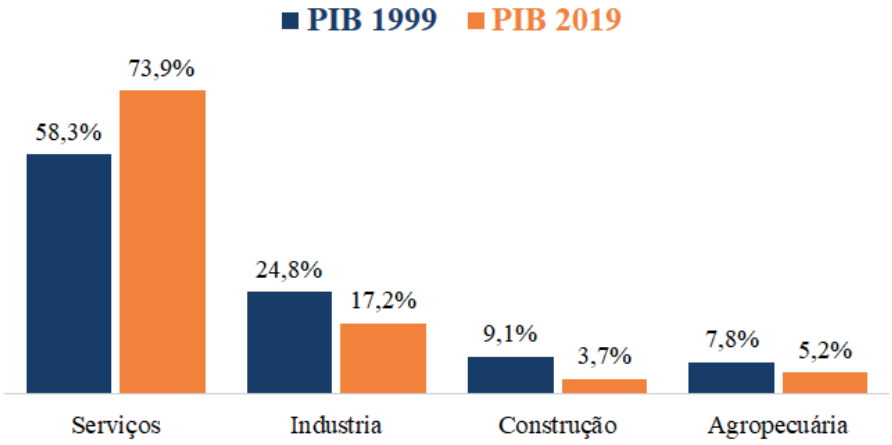

Fig. 3. PIB do Brasil divido entre os setores da economia. Fonte: [10].

Quando se fala em serviços, não se pode esquecer a quem ele é destinado. Sim, o cliente, mas quem é o cliente ou melhor o que é um cliente? Para algumas empresas, a razão de existirem. Para outras empresas, um objetivo a ser alcançado e mantido.

Historicamente houve algumas fases bem distintas quanto a produção de produtos ou serviços. Segundo [1], no início, o artesão supria as necessidades especificas de seus clientes, que ditavam com previsão a forma e as características do produto que encomendavam. Com advento da Revolução Industrial, surgiu a necessidade de padronização dos produtos e processos. Assim, o consumidor perdeu o poder de influenciar na definição dos produtos que iria consumir, ficando este com os projetistas, que, em regra, não consultavam o mercado quanto às suas necessidades.

Construir a satisfação do cliente por meio da qualidade e valor é o ponto chave do novo pensamento mercadológico. E esse pensamento parte da premissa básica de que os consumidores comprarão da empresa que entregar o maior valor. Assim, a oferta de produtos, ou serviços de maior valor, para o cliente passou a ser o diferencial que determina a vantagem competitiva em relação a outras organizações [11].

De todos os fatores capazes de determinar o sucesso de um empreendimento, ter uma boa ideia é, geralmente, considerado o mais importante, porém, atender bem o cliente é fundamental para alavancar a empresa. A sobrevivência e o sucesso de uma organização estão diretamente relacionados à sua capacidade de atender às necessidades e expectativas dos clientes, as quais devem ser identificadas e entendidas [12].

Um dos pilares da revolução digital no setor bancário é a *user experience* (experiência do usuário) e nela, os clientes passam a não mais comparar a experiência bancária somente entre os bancos, mas também com outras empresas de tecnologia e esperam mais [13].

A empresa que for realizar o serviço de atendimento ao cliente pelo modelo de telemarketing receptivo (tanto de ligações receptivas como de *backoffice*), precisará se preparar adequadamente para o volume de contatos/demandas que irá receber[14].

No caso do banco privado estudado neste trabalho, o atendimento ao cliente é feito por intermédio de um *backoffice* terceirizado. Como justificativa para tal escolha, [14] escreveu que o principal motivo é permitir que a empresa contratante do serviço, no caso o banco privado, possa focar em suas competências essenciais como emprestar dinheiro aos clientes, por exemplo.

3 Método de Pesquisa

3.1 Método de Pesquisa-ação

Para lidar com dados qualitativos da abordagem do problema desse estudo, será utilizado o método de pesquisa-ação para mapear, descrever e sugerir mudanças, se necessárias, nos processos dos departamentos do banco privado.

A pesquisa-ação é um tipo de pesquisa social com base empírica que é concebida e realizada em estreita associação com uma ação ou com a resolução de um problema coletivo e no qual os pesquisadores e o participantes representativos da situação ou do problema estão envolvidos de modo cooperativo ou participativo [15]. O detalhamento das etapas desta pesquisa pode ser observado na Fig. 4.

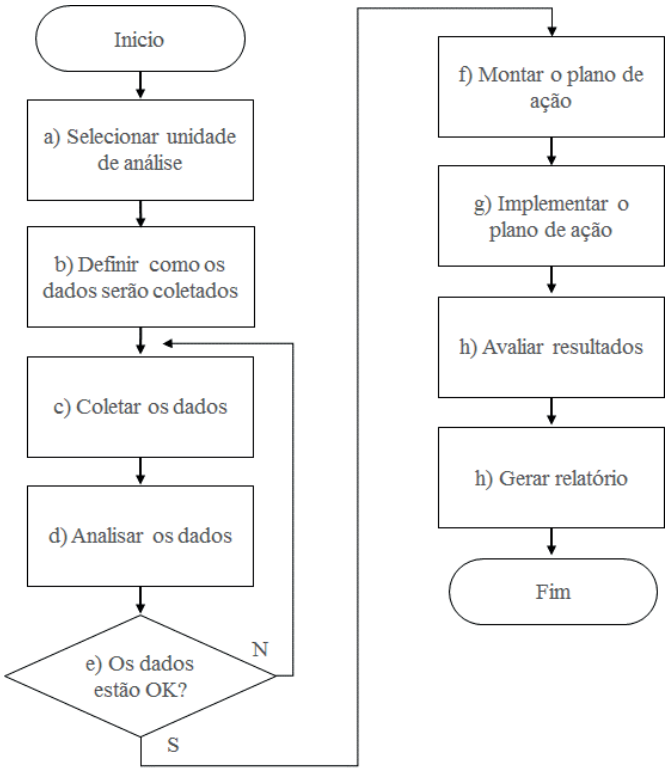

Fig. 4. Fluxograma da pesquisa

O principal foco da pesquisa-ação é a obtenção da perspectiva dos elementos que integram o objeto do estudo. Para uma abordagem mais positivista do procedimento, as variáveis devem ser controladas, as relações de causas/efeitos mapeadas e as condições de replicação da pesquisa bem detalhadas. A pesquisa-ação deve focalizar no problema real abortado no estudo, descrevendo as atividades necessárias para sua solução e relação entre os colaboradores [15].

3.2 Objeto de Estudo

Quando O banco privado deste estudo, está entre os 5 maiores bancos brasileiros e possui um grande portfólio de produtos e serviços financeiros, que são oferecidos diariamente aos seus clientes, tanto do tipo pessoa física como pessoa jurídica. Devido à grande quantidade de produtos e serviços financeiros oferecidos em seu portfólio, o banco privado é considerado do tipo misto ou múltiplo. Os principais serviços/produtos oferecidos são conta corrente, conta poupança, cartão de crédito, empréstimos/financiamentos, seguros e investimentos.

O banco privado do estudo, por ser tipo múltiplo e ter um porte muito grande (mais de 90 mil funcionários), apresenta muitos departamentos com produtos, serviços, fluxos, processos e formas de trabalhar diferentes uns dos outros, como se fossem

empresas diferentes dentro de uma mesma empresa e isto, gera um grande desafio para os gestores da alta administração. Logicamente, todos os departamentos seguem as normas pré-estabelecidas que regulamentam a atividade bancária, tanto internas como externas, mas mesmo assim, existe esse desafio a ser superado diariamente e de forma continuada pelos gestores.
Por conta da situação acima mencionada, este estudo foca no produto Empréstimos para pessoas do tipo Física e na modalidade Crédito Consignado, onde o cliente faz o empréstimo no banco e o valor da parcela é descontado diretamente de seu salário ou de sua aposentadoria [16].

Analisando os dados financeiros do banco privado, que foram publicados para os investidores após o último trimestre de 2019, foi constatado que a carteira de Crédito Consignado para pessoas física, representava 7% de todo o valor emprestado pelo banco e 20,6% de todo valor emprestado para pessoas física, mostrando sua importância para rentabilidade financeira da empresa.

4 Proposta de Implantação do IBP

4.1 Mapeamento do Fluxo de Trabalho

Para mapeamento do fluxo de trabalho deste estudo, foi utilizada a técnica de fluxograma apresentada por [17], pois, permite desenhar o fluxo de trabalho deste estudo, de forma simplificada e de fácil entendimento. O fluxograma tem como característica, apresentar poucos símbolos padronizados para sua utilização.

Através de reuniões presenciais ou por telefone com membros das equipes dos três departamentos envolvidos pelo estudo e utilizando a técnica de fluxograma, foram criados os fluxos de trabalho apresentados nas Fig. 5 e 6. O fluxograma da Fig. 5, apresenta o cenário atual dos departamentos do banco privado, que serão alvos deste estudo.

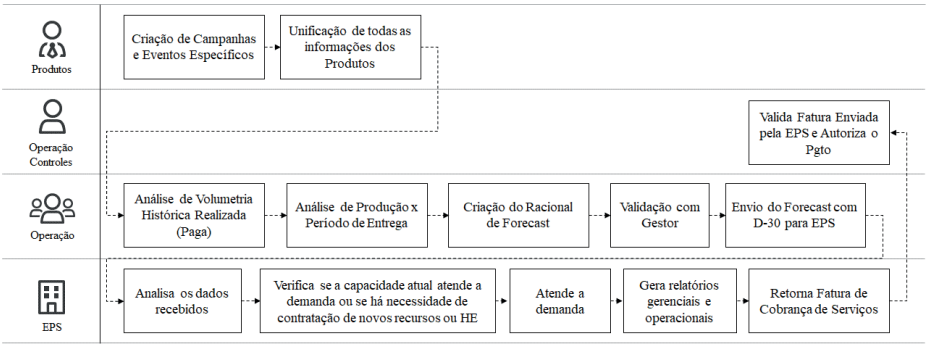

Fig. 5. Fluxograma antes intervenção do estudo

A informação inicial que compõe a previsão de demanda que é enviada para EPS, tem sua origem na área de produtos do crédito consignado, onde eram criadas todas as campanhas ou eventos para o produto. A equipe de pricing da área de produtos do crédito

consignado, era responsável por projetar e consolidar todas as volumetrias esperadas de novos contratos de crédito consignado por segmento, que o banco privado esperava adquirir por conta das campanhas ou eventos de vendas previamente agendadas e divulgadas. Esse plano ganhou o nome de carteira de clientes. Após o alinhamento, o plano era encaminhado via e-mail para os gestores e para área de operação, utilizarem os dados em suas previsões.

A área de operação com a posse do plano (carteira de clientes), analisava os dados e criava previsões que correlacionavam a volumetria histórica recebida pela EPS com a volumetria apresentada pela carteira de clientes. As previsões enviadas para EPS, eram somente dos próximos três meses. Uma vez montado o racional que seria utilizado na previsão de demanda, era realizada uma reunião com o gestor ou representante da operação para validação das volumetrias projetadas. Validados os dados, era enviado a previsão final para EPS através de e-mail e serviria para formalização oficial do plano entre o banco e a EPS.

EPS de posse da previsão enviada pelo banco, analisava a previsão e verificava se sua capacidade operacional estava adequada para atendimento da demanda. Se ela identificasse que existia um aumento ou redução da volumetria apresentada na previsão enviada pelo banco, a EPS precisava determinar se o evento é pontual (somente um ou dois meses) ou definitivo (novo padrão de volumetria média).
Se a demanda fosse alta e pontual, a EPS perguntava ao banco se podia fazer horas extras para atender a demanda, caso contrário, haveria impacto de SLA. O banco autorizando, eram feitas horas extras para atendimento da demanda. Se a demanda fosse baixa e pontual, a EPS agendava algum treinamento para o período ou dava férias para os colaboradores ou utilizava os recursos em outras esteiras de atendimento se fosse possível.

Se a demanda fosse alta e definitiva (os três meses com aumento), a EPS contratava novos recursos e solicita horas extras até que os recursos estivessem disponíveis para o atendimento. Se a demanda fosse baixa e definitiva (os três meses com redução), a EPS realocava os colaboradores para outras esteiras.

Após o atendimento da demanda e no próximo dia, a EPS disponibilizava os relatórios gerencias e operacionais para consulta. Após o fechamento do mês, a EPS informava a volumetria oficial tratada no mês e enviava a nota fiscal para o banco com todos os serviços prestados. A área de controles do crédito consignado junto com a operação, validavam a fatura e liberavam o pagamento para EPS se a cobrança estivesse correta.

No processo de mapeamento do fluxo de trabalho, foram identificados alguns itens dos processos que podem ser melhorados: falta de uma reunião de S&OP, falta de *Hard Skills* especificas de previsão de demanda, falta de métricas de gerenciamento de demanda, falta alinhamento dos planos financeiros com os planos de S&OP, prazo para envio da previsão de demanda elevado, falta de um *software* integrado de S&OP.

4.2 Proposição do processo IBP

No novo fluxo de trabalho. foram feitas mudanças para melhorar a entrega final e corrigir os problemas apontados no item anterior. Na Fig. 6, tem-se o novo fluxo de trabalho que foi implantado no banco.

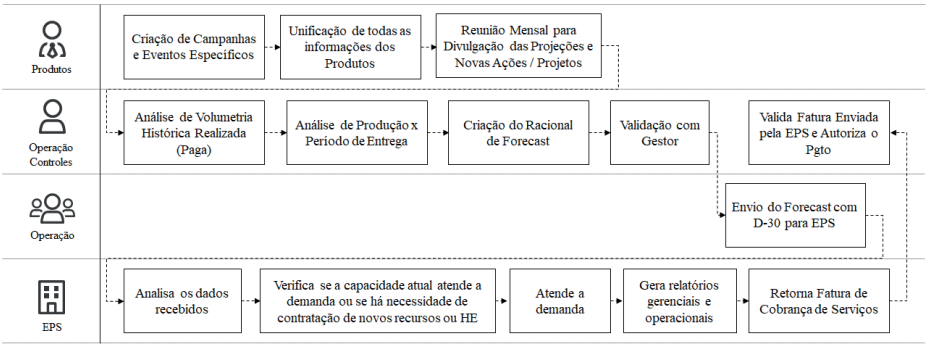

Fig. 6. Fluxograma após intervenção do estudo

Foram feitas as seguintes mudanças no fluxo de trabalho para resolver os problemas relatados:

Falta de uma reunião de S&OP: Foi alinhado com a área de pricing, que seria realizada uma reunião mensal para divulgação da previsão de carteira clientes e alinhamento das expectativas. Nessa reunião deveria ser apontado toda e qualquer informação nova sobre projetos ou eventos que poderiam impactar a demanda e se necessário, efetuar mudanças na previsão criada.

Falta de Hard Skills especificas de previsão de demanda: aqui havia duas soluções possíveis. A primeira era treinar os colaboradores em conhecimento de modelagem estatística e a segunda, era transferir a atividade para outra equipe. Foi ponderado os pontos fortes e fracos de cada uma e optou-se pela segunda alternativa, que era passar o processo para área de controles, uma vez que a área já tinha o conhecimento especifico em modelagem estatística. A única exigência era que a previsão fosse validada com os gestores da operação ou pontos focais da operação e que após a validação, a operação mandasse a previsão para EPS, por conta do relacionamento direto com eles.

Falta de métricas de gerenciamento de demanda: foi solicitado a equipe de pricing, que realizasse uma apuração do % de acuracidade dos dados que eles estavam gerando em suas previsões da carteira de clientes e de forma pontual, os dados foram gerados e houve a constatação que sua acuracidade não estava ideal (acima de 20% de erro percentual). Por enquanto, a equipe ainda não adotou o indicador como forma de balizar a qualidade das previsões, mas para as próximas reuniões, será solicitado que o indicador seja incluído em suas metas administrativas.

Falta alinhamento dos planos financeiros com os planos de S&OP: após a constatação da situação na área de controles e como o as previsões de demandas passaram a serem feitas na área, houve uma integração das previsões de volumetria de demanda com o orçamento e acompanhamento dos custos financeiros da superintendência como um todo. A criação de cenários hipotéticos de impactos financeiros foram tiveram seus tempos reduzidos por conta da informação estar integrada.

Prazo para envio da previsão de demanda elevado: como o prazo de previsão que o banco deveria enviar a projeção para EPS era de 45 dias de antecedência ao mês de trabalho e havia ainda a multa de garantia de atendimento de 90% da demanda deveria ser paga, independente do volume ser menor do que 90% da previsão formalizada, a

área de operação conseguiu negociar junto com a área de compras e a EPS, uma redução no prazo, onde o tempo de envio da previsão seria de 20 dias de antecedência ao mês de trabalho e não mais 45 dias. Por conta dessa situação, houve ganho de acuracidade na previsão de demandas por ser possível ter dados mais recentes da situação do produto e o horizonte de planejamento ser menos longo.

Falta de software integrado de S&OP: foi levado esse assunto para os gestores da operação, mas por envolver custos de licenças e mudanças de atividade, está em análise ainda.

5 Conclusões parciais e próximas etapas do trabalho

Os objetivos específicos deste estudo foram atendidos. Foi realizado o mapeamento do fluxo de trabalho entre os departamentos do banco privado e isso resultou na identificação de processos passiveis de melhorias imediata.

As mudanças implementadas, melhoraram as relações de trabalho entre as áreas, unificaram boa parte dos planos operacionais e financeiros dos departamentos, e já estão contribuindo para melhorar a margem financeira do banco privado. Mesmo assim, existem muitas oportunidades que possam ser estudas e implantadas no fluxo de trabalho.

Para próxima fase deste estudo, espera-se demonstrar a aplicação do modelo de maturidade, para medir o conhecimento das práticas de S&OP e IBP dos departamentos do banco privado, e assim, propor novas soluções para otimizar os processos e conduzir a implementação de forma consistente das melhores práticas S&OP e IBP.

Finalmente, espera-se que este estudo contribua para a comunidade acadêmica com relatos de experiências reais sobre implementação dos processos de S&OP e do IBP, em bancos privados.

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Application of the AHP method to assist the strategy of bike share station positioning in the city of São Paulo

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Abstract. This article investigates the bicycle allocation strategy in a competitive market of bicycle sharing at autonomous stations. The data scientist seeks to understand the market in the shortest possible time, while the customer wants to obtain the best experience of integrated use between the different modes of transportation. The initial position of bicycle stations, the coverage area and the allocation method are investigated, and with the assessment by mobility specialists or customers, the AHP method is fed, whose results combined with the previous data are grouped into clusters to detect the best and worst bike share stations. The case study was performed with real data from a bicycle sharing network in the city of São Paulo to demonstrate the effectiveness and feasibility of the proposed solution. The results show that the proposed method was able to quickly identify the efficiency of the position of bike share stations, enabling their further optimization.

Keywords: bike share, data mining, AHP, model evaluation

1 Introduction

Around the world, bicycles are considered practical and reliable. Far from being a leisure-only option, they are currently used as a means of urban transportation where many cities face serious mobility problems. In Brazil, most cities face a scenario with serious problems where transportation by private motor vehicles causes major congestion and more pollution. Public transportation, on the other hand, offers users low connectivity, but presents an opportunity for the connection between different modes of transportation and increases the quality of user satisfaction. Seen as a strong candidate to help change perception and transportation habits over short distances, collaborative consumption through the sharing of bicycles and scooters has been gaining strength and fans. It is seen as an inexpensive, efficient and healthy way to navigate dense urban environments [14].

This work aims to analyze the strategic positioning of bicycle sharing stations with a focus on traveling between stations and other modes of public transportation using data mining techniques and the AHP decision-making method.

Collaborative consumption can be seen as a return of the old practices of sharing, collateral, rent and exchanges, which were the first forms of commerce but were abandoned with the advent of the capitalist model of production [2].

Currently the big difference is the technology that, through online platforms, smartphones and IoT devices, makes it possible to connect people to smart devices or stations powered by solar energy, GPS and RFID systems that allow better management and control of the vehicles.

The technology called IoT (Internet of Things) connects smart sensors or hardware to the internet [1]. Big Data Analytics (BDA) and the Internet of Things (IoT) are being considered the most profound transitions in technology [12] [9]. For example, in modern factories, large volumes of records and information are generated by sensors embedded in machines that are connected to solutions based on cloud processing. The main objective of adopting IoT in factories is to transform them into "smart factories", where machines and devices communicate with each other and are connected in a network [12], increasing agility and reducing costs. For some time now, research has shown how organizations that rely on collected data take advantage of information as a competitive advantage [18].

In smart cities, two items are considered essential in most analyses: the aspects of transportation and logistics with a predominantly sustainable point of view, and new technologies to facilitate the organization of activities, including data capture and analysis. Along with this change comes a growing "social pressure" from the city's public institutions on companies to design more sustainable transportation networks [6]. Thus, it is becoming clearer that it is necessary to understand and analyze the experience of consumers in e-commerce or traditional retail stores. Future logistics networks in smart cities will need to support omni-channel models. Therefore, it is essential to map the activities and the integration between various points of contact of the consumer and the brand during the shopping experience [4].

This work proposes an approach that combines the K-Means unsupervised learning method with the application of the Multi-criteria Decision Making (MCDM) method known as AHP (Analytic Hierarchy Process) to evaluate qualitative parameters in the various bike share stations in São Paulo with statistical information from 2017. In order to achieve this goal, the following is sought:

- Create a method for the quantitative analysis of bike share stations;
- Consider the role of the specialist or customers in the method;
- Use machine learning and data mining methods to compose the flow of the proposed method;
- Suggest the optimization or readjustment of stations with poor evaluation results;

AHP [15] is a method that makes it possible to deal with many decision criteria through pairwise comparisons, facilitating an assertive and personalized choice for a specific context. This method was chosen because it is a tool that is already consolidated and applied as a scientific basis containing various relevant applications and publications as in [5].

The weights generated at the end of the multi-criteria method serve to qualitatively evaluate the obtained clusters. Thus, taking the knowledge of experts and business model rules to interact directly with a machine learning algorithm. This information can help optimize docking points, making it possible to remove inefficient points, for example.

In view of the various sources used to populate the variables of the problem, a new dataset called bike_station_dataset was created, which groups information from bike share docks together with subway stations, geolocalized population information, relief information and bike paths.

2 Bike sharing worldwide

Paris and Barcelona installed their bicycle sharing system in the same year (2007), initially with few stations [10]. In 2013 there were already around 540 bike sharing programs worldwide in 50 countries with a total of more than 500 thousand bicycles, representing about 2 million trips a day in cities like Wuhan, Shanghai, Hangzhou and Taiyuan in China, as well as London, New York and Montreal [11].

Like bicycles and motorcycles, cars are used in the urban environment in what is known as door-to-door transportation. In 2012, bicycle sales exceeded car sales in 25 of the 27 European Union countries, which was economically justified due to the severe crisis there. The increase in bicycle sales was also justified by the adoption of broad public policies to encourage the use of bicycles and the construction and maintenance of bike paths.

3 Methodology

Previous studies have listed possible evaluation parameters for similar topics. For example [7] makes a similar analysis with AHP in the Mashhad region in Iran. The work gathered data from various open sources to group parameters that could be qualitatively representative to evaluate a bike share station.

For this case study the following factors are considered:

- Proximity to subway stations;
- Distance between bike share stations;
- Population of the region;
- Relief variation;
- Proximity to bike paths.

Proximity to subway stations: One of the important goals that bike share stations are solving is the "last mile" problem, a name given to the short distance to ride a bike between transit stations and home, the workplace, university, etc. [3]. It is of great importance and essential for BS systems to be integrated with other modes of transportation for the efficiency of the system as a whole, and many cities are looking for this model [17]. However, it is important to note that

efficiency and integration with different transportation models is not the only factor for the success of the BS system. In this work, information was used on the geopositioning of all subway stations in the city of São Paulo, available on Kaggle [1]. For each bike station, the nearest subway station was selected in a straight line.

Distance between bike share stations: many researchers have pointed out the importance of adequate spacing between stations [13]. In fact, the short distance to be traversed between stations is one of the keys to success. This together with a balanced distribution of stations can guarantee that everyone has the right to access the bikes [7]. From the geopositioning of the bicycle stations, a comparison of one station with the others was carried out to find out if there was a station within a close distance to integrate bicycle transportation on bike paths.

Population of the region: a study on the city of Lyon, France, shows that the population is among the important factors that affect the long-term use of bicycles by permanent users [19], as well as in Guangzhou, Chine, where 40 % of bike use comes from stations near people's homes [17]. Here, to determine population density, IBGE data was collected in the form of a statistical grid for polygons within the city of São Paulo.

Relief variation: stations at a higher altitude are less likely to be part of the users' route or to be visited. In this case study, the geotechnical chart or topographic map of the city was taken into consideration, and according to this, the highest stations are less attractive to users. It is also noted by [11] that the stations at high locations are empty of bicycles and the stations at low altitudes are full of them.

Proximity to bike paths: bearing in mind that bike paths are essential for the functioning of the bike share system, each station must be strategically positioned to integrate the stretches between public transport stations. The feeling of safety on the bike path is very important to encourage people to use bicycles [8].

For the case study in the city of São Paulo as well as other cities worldwide, the data for the factors listed above are publicly available, and the model can be applied in other locations.

Thus, with the processed and tabulated data, a dataset was generated, which will be subjected to the K-means clustering technique. This technique uses optimization to try to separate the samples into k groups of equal variance, varying the k-centroids iteratively in order to minimize the intra-cluster distance [16].

At the same time, an MCDM process was carried out using the AHP method in view of the observations made about the parameters mentioned in the literature, mainly in [7]. The weights resulting from the AHP method thus serve to evaluate the clusters obtained by the algorithm, enriching the computational operation with the information provided by specialists. The complete flow can be seen in Figure 1.

[1] São Paulo subway stations, dataset. Available at: https://gist.github.com/rafaelrinaldi/6a82dd1eceed6dfc7deb. Accessed 01/03/2020.

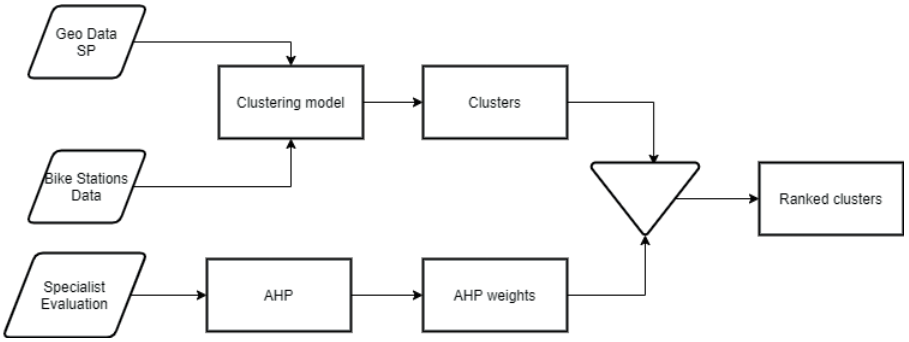

Fig. 1. Information flowchart for the proposed methodology

4 Area in analysis

The geographic area under study comprises the city of São Paulo, with an estimated population of 12,252,023 inhabitants. It is a city with a good variety of urban transportation modes such as buses, bike paths, and subway and train lines. As population density is a potentially relevant factor, this information was extracted through IBGE, which publishes granular data by census sector. Information was also collected on the relief of the city of São Paulo based on the geotechnical chart available in the city hall's open data portal.

The city of São Paulo has 473.3 kilometers of bike path, being the 6th city in the world ranking of the 50 cities with the highest mileage. For cyclists to take advantage of the modal integration, there are more than 8 thousand bike spaces in hundreds of public bicycle stands, which are installed in bus terminals, train and subway stations, and Traffic Engineering Company (CET-SP) parking lots.

There are few sources of data on bicycle stations in São Paulo, so for this study we adopted the database available on the Kaggle [2]. The dataset has a historical record of the availability of bicycles at stations in the city, and thus the bike share stations were mapped.

The bike path network [3] mapped by the city of São Paulo and the Traffic Engineering Company (CET-SP) is available free of charge in vector format. This municipal bike path network is constituted by road interventions dedicated to the exclusive circulation of bicycles. These consist of bike paths, bike lanes, shared sidewalks, and bike routes.

Subway stations are available in the Github project repository [4], as well as their respective names, geolocation, address and operating hours.

[2]Bike sharing SP Database. Available at: https://www.kaggle.com/marlesson/bicycle-sharing-brazil-sp-gyn. Accessed on 02/03/2020.

[3]São Paulo bike path network. Available at: http://www.cetsp.com.br/consultas/bicycling/mapa-de-infraestrutura-cicloviaria.aspx. Accessed on 03/02/2020

[4]Dataset of SP subway stations. Available at https://gist.github.com/rafaelrinaldi/6a82dd1eceed6dfc7deb. Accessed on 03/02/2020.

5 Results

The evaluator considered the relationship between 5 variables, which are: Proximity to subway stations; Distance between bike share stations; Population of the region; Relief variation; Proximity to bike paths. The comparisons are made in pairs to calculate priorities using the Analytical Hierarchy Process (AHP).

Table 1. Comparison between the variables analyzed by the specialist.

A - AHP priority - B			Evaluation
1	Proximity to subway stations	Distance between bike share stations	2
2	Proximity to subway stations	Population of the region	3
3	Proximity to subway stations	Relief variation	6
4	Proximity to subway stations	Proximity to bike paths	9
5	Distance between bike share stations	Population of the region	2
6	Distance between bike share stations	Relief variation	5
7	Distance between bike share stations	Proximity to bike paths	6
8	Population of the region	Relief variation	3
9	Population of the region	Proximity to bike paths	5
10	Relief variation	Proximity to bike paths	5

Given the variables, a total of 10 questions were generated for paired comparisons. The paired comparison of all criteria is made with respect to the AHP priorities, evaluating the criterion A vs. B on a scale of 1 to 9, with 1 being the same level of importance and 9 being the absolute importance of criterion A in relation to B. These are the resulting weights for the criteria based on their comparisons:

Table 2. Ranking of weights for each criterion based on the AHP method in priority order.

Variable	Priority	Rank	(+)	(-)
Proximity to subway stations	43.9 %	1	9.0 %	9.0 %
Distance between bike share stations	27.7 %	2	8.3 %	8.3 %
Population of the region	16.6 %	3	4.3 %	4.3 %
Relief variation	8.4 %	4	4.6 %	4.6 %
Proximity to bike paths	3.4 %	5	1.2 %	1.2 %

The geolocalized data obtained was grouped by the creation of a hexagonal grid with a 2 km circumscribed radius. In this way, the Population variable was grouped with a sum and the relief variation was adjusted with the average presented in each hexagon, creating a region of influence more relevant to the context of the docking stations.

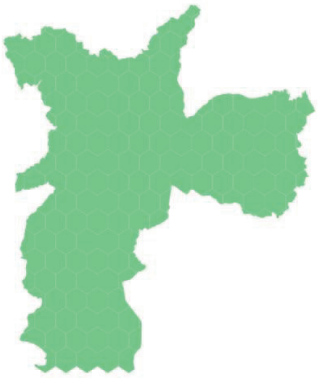

Fig. 2. Map of the city of São Paulo with the Hexagonal Grid

With the dataset already built, the clustering process continued, where several K values were tested, but what appeared to have the best performance according to the silhouette coefficient was the value 4, as can be seen in Figure 3.

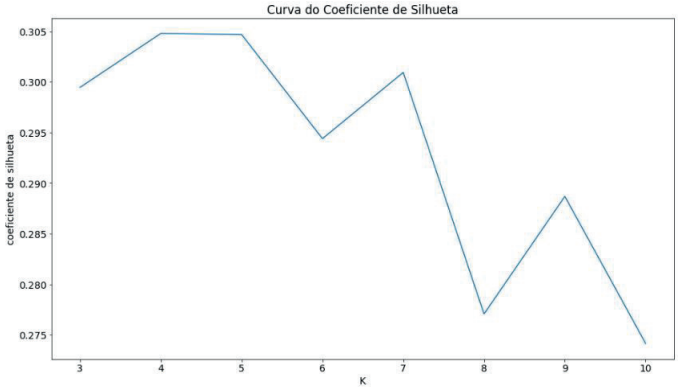

Fig. 3. Silhouette coefficient curve for the different k values

With the obtaining of k = 4 groups of stations, the determination of the product of the parameter values with the weights generated by the AHP model was carried out, inverting the module of the features whose growth implies negative consequences for the cyclist's experience. Thus, a score was obtained that allowed the comparison of the groups in a practical and simplified way, as shown in Figure 4.

It is observed in figure 4 that cluster 0 appears to present the best results, considering that all of its quartiles are above those found in the other groups.

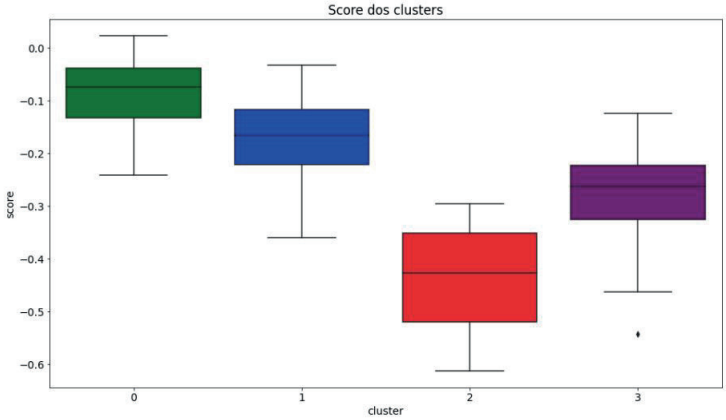

Fig. 4. Visualization of the cluster evaluation

Thus, the geographic positioning of the clusters is shown in Figure 5, using the same colors of figure 4 to identify which cluster the station belongs to. The stations in green are considered more attractive and are visibly concentrated in the more central areas, which have high population density and flow of people. In addition, these zones have stations close to each other and a good proximity to subway stations, the two most important factors pointed out by the AHP method.

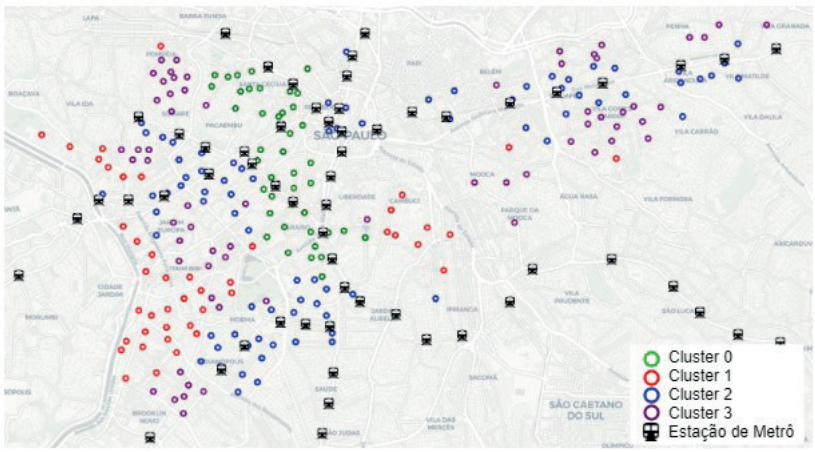

Fig. 5. Geographic location of the obtained clusters (circles) and subway stations (icon)

At the same time, it is noted that group 2 (red), which has the worst score evaluation, has a notable presence in more distant areas with greater distance between stations. It is also noticed these bike share stations are a great distance from subway stations, hindering an integration between these modes.

6 Conclusion

In view of the results achieved, it can be said that the methodology proposed in the present work achieved its objectives, carrying out a quantitative analysis of the stations with the possibility of combining this data with a qualitative view from a specialist and/or a user. The MCDM resource was combined with an unsupervised learning technique, generating groups easily distinguishable by the different distributions of their variables and by the score obtained for each variable using the AHP method.

Thus, the best and worst groups were indicated by the clusters' scores, as well as patterns that differentiate them, explaining the relevance of some of the parameters provided by the decision method, such as the distance to other stations, which penalizes more isolated stations such as those in group 2 of figure 4.

The role of the specialist or client is considered as an essential evaluator for the operation of the method, as it provides a subjective and qualitative view, in addition to the possibility of adapting to different regional and temporal contexts.

Future works can apply the proposed model in other cities around the world and propose new parameters to evaluate the stations. Further investigation with urban mobility specialists can enrich the work and bring it closer to the local reality. Tests with other methods such as PROMETHEE can also be performed.

Other analysis possibilities can arise when adding more parameters about the stations and their surroundings to create an even more robust dataset and test other types of clustering algorithms. A comparative approach with the results presented in this article can also be carried out.

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Hacia el desarrollo de una movilidad inteligente para la ciudad de Bahía Blanca: Primer enfoque sobre la caracterización de la flota vehicular del microcentro.

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Resumen. En este estudio se presentan los resultados preliminares obtenidos del análisis del flujo vehicular y su correspondiente segmentación, en determinadas intersecciones del microcentro de la ciudad de Bahía Blanca durante el primer trimestre del año 2020. Los datos generados en este trabajo son de vital importancia para, en un futuro, ser empleados en el modelado de la dispersión de las emisiones generadas por fuentes móviles en el microcentro de la ciudad de Bahía Blanca. Además, la generación de datos fidedignos contribuirá con las autoridades locales para la toma de decisiones tendientes a realizar una gestión inteligente del tránsito. Se exhibe la composición de la flota vehicular, así como también la antigüedad promedio de los vehículos motorizados que circulan por las calles evaluadas. Los datos de caracterización de la flota vehicular fueron generados mediante el análisis del material fílmico producido para este fin. Los videos examinados fueron confeccionados en el marco de nuestra investigación en cuatro puntos clave, en tres momentos del día (mañana, mediodía y tarde) en los meses de enero y marzo (pre-COVID-19) del año 2020. Esta investigación ha permitido mostrar una diferenciación en el flujo vehicular entre ambos meses en estudio siendo marzo el mayor. Además, se observó que el vehículo con más predominancia en circulación para ambos meses es el denominado sedan o automóvil particular. Finalmente, se comprobó que la antigüedad del parque automotor de la ciudad es un 17% más nuevo que el reportado a nivel nacional.

Palabras claves: Flujo vehicular, Bahía Blanca, Transporte carretero.

1 Introducción

Una ciudad inteligente es aquella que contiene múltiples atributos, la mayoría presenta cuatro características principales: sustentabilidad, calidad de vida, urbanización e inteligencia. Esta última se define como el deseo de mejorar los aspectos sociales, ambientales y económicos de la ciudad y sus habitantes. Por lo tanto, una ciudad inteligente es

aquella que posee una visión a largo plazo sobre el mejoramiento del área urbana, con el objetivo de reducir la contaminación ambiental y propiciar una mejor calidad de vida para los ciudadanos. En este aspecto, la movilidad es uno de los temas más difíciles de enfrentar en áreas metropolitanas dado que, involucra tanto aspectos ambientales como económicos [1, 2].

La movilidad de personas y bienes es fundamental para el desarrollo de las ciudades y la sociedad. El crecimiento tanto económico como poblacional conllevan un aumento significativo en la movilidad. El gran volumen y la variedad de actividades que el transporte apoya sirven para destacar el rol positivo que desempeña en nuestra sociedad. Sin embargo, el sector de transporte tiene impactos negativos tanto en el medio ambiente, en la sociedad como en la economía, tales como: generación de contaminación, congestión en las calles, alto costo de los servicios públicos de transporte local, etc. Es la presencia de estos impactos negativos lo que genera la necesidad de gestionar y supervisar eficientemente el tránsito, el cual ha aumentado en las últimas décadas. Por lo tanto, el tópico de movilidad inteligente es uno de los temas más prometedores dentro del horizonte de una ciudad inteligente, ya que podría producir grandes beneficios para mejorar la calidad de vida de casi todas las partes que conforman una ciudad [1, 3, 4].

El desarrollo de una movilidad inteligente impacta directamente en la calidad de vida de las personas que viven en las ciudades. Es por ello que si se quiere generar acciones tendientes al diseño de una movilidad inteligente es necesario estudiar el tránsito. Un primer paso en este estudio consiste en generar un análisis del flujo de tráfico, en el cual se estudian las interacciones entre las partes que lo componen como, por ejemplo: tipo de conductor, vehículos, pasajeros/vehículo, calles, señalización, etc. El objetivo es comprender cómo se mueven los distintos medios de transporte dentro de la ciudad, pudiendo detectar problemas de congestión, entre otros, y optimizar el flujo vehicular permitiendo un movimiento más eficiente de personas y vehículos. Como es sabido, el tráfico varía de un lugar a otro, difiriendo en volumen y en tipo de vehículos que circulan, por ejemplo, una calle céntrica puede tener un gran volumen de vehículos por día, siendo en su mayoría automóviles. Es por ello que la recopilación de datos permite obtener el volumen de vehículos, así como también generar una clasificación por tipo de unidad [1, 5, 6].

Las ciudades pequeñas y medianas de países sudamericanos, que sirven como intermediarias presentan un rápido crecimiento y urbanización, en algunos casos se han desarrollado de forma desmedida y sin planificación fomentando la teoría del tránsito inducido, la cual establece que el mejoramiento y expansión de la infraestructura de accesibilidad a la ciudad conduce a fomentar un mayor uso del automóvil particular. En busca de una ciudad inteligente, se debe trabajar en políticas de transporte y desarrollo urbano, con el fin de reducir los niveles de contaminación atmosférica y de ruido [7, 8, 9, 10].

El caso de estudio presentado corresponde a la ciudad de Bahía Blanca, la cual se encuentra emplazada al sudoeste de la provincia de Buenos Aires, Argentina; es un conglomerado urbano que ocupa una superficie de 2247 km^2 y cuenta con 301572 habitantes [11] (Fig. 1), debido a estas características puede ser considerada como una urbe de mediano tamaño. Además, dado que la ciudad alberga un puerto, el mayor cen-

tro petroquímico del país y un gran parque industrial puede ser catalogada como intermedia, dado que presenta los atributos de ser un nexo entre sus alrededores [12]. La ciudad de Bahía Blanca ha presentado un constante crecimiento de su área urbana, registrándose un incremento de la extensión de la ciudad del 110% entre los años 1986 - 2014, extendiéndose en diversas direcciones. Debido al significativo crecimiento económico de la ciudad se ha generado una expansión del desarrollo urbano no planificado, lo cual se relaciona con el aumento de la movilidad mediante el uso de vehículos motorizados. En una encuesta preliminar realizada por nuestro grupo de investigación se destacó que, entre el 70 y 80 por ciento de la población local, considera que el tránsito vehicular se vio incrementado en la ciudad, ocasionando un impacto negativo sobre el ambiente [10, 13, 14].



Fig. 1. Localización de la ciudad de Bahía Blanca, al sudoeste de la provincia de Buenos Aires, Argentina.

Dado que, la ciudad de Bahía Blanca pretende convertirse en una ciudad inteligente [15], consideramos que es de importancia empezar a estudiar el flujo vehicular local de manera detallada considerando la segmentación. Por lo tanto, dado que nuestra motivación es acompañar este desarrollo hacia una movilidad inteligente [16, 17], en el presente trabajo mostramos los resultados alcanzados hasta el momento acerca de la caracterización de la flota vehicular en el microcentro de la ciudad. Para lo cual se siguió una metodología de conteo y segmentación manual a través de la visualización de videos filmados en tres rangos horarios (mañana, mediodía y tarde) en un mismo día

entresemana de los meses de enero y marzo (pre-COVID-19) del año 2020, en cuatro puntos representativos del microcentro.

El objetivo principal del presente trabajo es generar datos confiables que serán en un futuro utilizados en el modelado de la dispersión de las emisiones generadas por fuentes móviles en el microcentro de la ciudad de Bahía Blanca, y contribuirán con las autoridades locales para la toma de decisiones.

2 Metodología

El estudio de la caracterización de la flota vehicular de una ciudad brinda información esencial que permite generar políticas y normativas con el fin de mejorar la movilidad. Además, una correcta segmentación del parque automotor es necesaria para estimar las emisiones locales debidas al tránsito, facilitando el control de los niveles de calidad de aire [18].

El presente trabajo se centra en el estudio de la flota vehicular (segmentación) y flujo de tránsito en cuatro puntos estratégicos del microcentro de la ciudad de Bahía Blanca. El actual análisis se realiza para dos periodos del año, en tres momentos del día: mañana, mediodía y tarde, considerando estos como los momentos de mayor tráfico. Con el fin de estudiar arterias de alta circulación en horarios pico, se seleccionan cuatro localizaciones estratégicas pudiéndose, en un futuro, analizar más. Dichos puntos se enumeran según se muestra en la Figura 2, siendo:

- Punto 1 (P1) la intersección entre calles Chiclana y Donado,
- Punto 2 (P2) la intersección entre calles Brown y Donado,
- Punto 3 (P3) la intersección entre calles Brown y O´higgins,
- Punto 4 (P4) la intersección entre calles Chiclana y O´higgins,

En cada uno de los puntos seleccionados se filmaron 3 videos cortos por día, de aproximadamente 7 cambios de semáforo por arteria, equivalentes a unos 7 minutos. En cada locación se obtuvo un video en horas de la mañana (8 am), otro al mediodía (12 pm) y un último a las 7 pm, siendo estos horarios los considerados como de mayor afluencia al microcentro de la ciudad.

La confección de los videos tuvo lugar el 7 de enero y el 9 de marzo del 2020 (pre-COVID-19). Las fechas fueron seleccionadas con el fin de presentar los cambios por estacionalidad y la actividad de un día entresemana. Como fue mencionado anteriormente el mes de enero es, en la ciudad de Bahía Blanca, un mes en el cual se produce el receso escolar y de muchas instituciones públicas, lo que conlleva una merma en el tránsito local, tal es así que el transporte público presenta bajas frecuencias de circulación. Por otro lado, en el mes de marzo comienza el ciclo lectivo escolar, así como también diversas actividades que incrementan el flujo vehicular. Esto es parte inicial de un trabajo que seguirá durante el año, con el fin de obtener una visión global de la fluctuación anual del flujo vehicular.

El material fílmico se generó con una cámara digital Samsung ST68 compacta de 16.1 Mega pixeles, obteniendo videos de resolución 720p (HD) - 1280 x 720 pixeles.

Las grabaciones fueron realizadas desde la vereda de una de las esquinas de cada intersección, la cual permitió obtener una visión completa del flujo vehicular de las dos arterias que componen el cruce (Fig. 3). Luego se procedió a realizar el conteo y segmentación del tráfico, lo que implica contar e identificar vehículos que pasan por un punto en el intervalo de tiempo del video (7 min aproximadamente), los detalles se explican en las siguientes secciones. Según la literatura este intervalo puede variar entre 24 horas por día, 365 días al año, a cinco minutos en una hora pico [19]. El conteo del tránsito es un dato base en el campo de estudio de la ingeniería del tránsito, tal es así que permite determinar el tránsito promedio diario en un determinado segmento de la calle, identificar en qué momento del día/mes/año ocurre el mayor volumen de tráfico, calcular la cantidad de kilómetros recorridos, etc. Los recuentos anuales o trimestrales permiten monitorear el nivel de congestión, evaluando si se está convirtiendo en un problema, con el fin de tomar medidas correctivas [19].

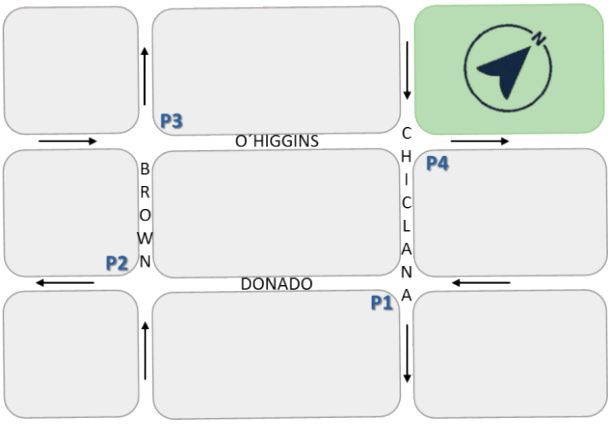

Fig. 2. Localización de las cuatro intersecciones donde se realizaron las filmaciones en el microcentro de la ciudad de Bahía Blanca, Argentina.



Fig. 3. Vista panorámica obtenida en las grabaciones de cada intersección en evaluación.

2.1 Segmentación de la flota por tipo de vehículo y análisis de la relación del flujo vehicular en cada intersección.

En la etapa inicial, los videos se observan por primera vez uno a uno, generando el conteo manual de la cantidad y tipo de vehículo que transita, obteniendo la catalogación del parque automotor en cada intersección, por día y hora. Las categorías en las cuales se desglosa la flota vehicular corresponden a: motocicletas, autos particulares (tipo sedán), camionetas, transporte de carga liviana y colectivos.

La segmentación se realiza de forma manual, dado que se pueden obtener buenos resultados con bajo margen de error, comparando resultados automatizados provenientes de softwares que detectan el largo del vehículo, lo cual en el presente trabajo no se realiza, sino que la categorización es por tipo de vehículo, permitiendo entonces un fácil reconocimiento [20].

Una vez obtenida la cantidad de unidades que contiene cada segmento, se utiliza la ecuación (1) para conseguir la cantidad de vehículos de cada categoría, que transita por cada arteria por minuto, en el día y hora especificados. Para ello se considera el tiempo que dura la filmación, el cual oscila entre 6 y 8 minutos.

$$V_{a,b} = \frac{U_{a,b}}{t_b} \tag{1}$$

Siendo:

$V_{a,b}$ la cantidad de vehículos de la categoría a que circulan por minuto por la arteria b;

$U_{a,b}$ la cantidad de unidades de la categoría a que circularon por la arteria b capturados en el video;

t_b el tiempo de duración del video, en minutos.

En esta sección se utiliza el análisis de la varianza (ANOVA simple) sobre los datos obtenidos con el fin de conocer si existen diferencias significativas del flujo vehicular primero entre los horarios de medición y segundo entre las intersecciones seleccionadas. Esto permite evaluar si el flujo en la cuadra del microcentro bahiense analizada es constante o varía significativamente. El estudio ANOVA se implementa usando el software InfoStat (http://www.infostat.com.ar/), con un p=0.05, y para las comparaciones múltiples se aplica el test de Fisher, el cual es adecuado para encontrar igualdades. Recordar que los puntos de estudio se eligieron porque tienen un comportamiento equivalente.

Como resultado de esta sección, se obtiene la categorización por tipo de vehículo en las localizaciones estudiadas, permitiendo evaluar la clase que más frecuentemente circula por cada intersección en cada horario y época.

2.2 Segmentación de la flota vehicular por antigüedad.

Una segunda visualización de las capturas filmográficas permite generar una segmentación aproximada por antigüedad, a través de la detección de la chapa patente identificatoria de cada unidad. Específicamente, en los videos se busca detectar el formato de la chapa patente, colores y forma, y en caso de ser posible la letra con la que comienza. Debido a que es muy difícil la correcta visualización del formato de la chapa

patente de las motos, estas no fueron consideradas en la segmentación, quedando entonces las categorías: autos particulares (tipo sedán), camionetas, transporte de carga liviana y colectivos.

En la Argentina, las chapas identificatorias de los vehículos han sufrido transformaciones con el paso de los años (Fig. 4). A partir del 1º de enero de 1995, se incorporó un nuevo sistema de patentamiento, el cual estableció que los dominios vehiculares estarían conformados por 3 letras iniciales y tres números, aquellos vehículos nuevos cuya inscripción inicial fuera después del 1º de enero de 1995 se le fueron otorgados dominios desde la patente *AAA-000*. En cuanto a los vehículos de modelos menores a 1995 se les solicitó el reempadronamiento de los mismos en el Registro Nacional de la Propiedad Automotor, otorgándoles los dominios a partir de *RAA-000*. Dado que, se preveía que en 2017 se alcanzaría el máximo número de combinaciones se optó por cambiar nuevamente el sistema. En 2014 se presentó una nueva patente, la cual sería única para todos los países que conforman el Mercado Común del Sur (Mercosur). Sin embargo, en la Argentina comenzó a implementarse recién en 2016 el patentamiento de vehículos nuevos, pero sin el reempadronamiento de los automotores usados que mantuvieron su patente original. Esta nueva chapa tiene características diferentes a la implementada con anterioridad dado que, cambia su forma, color y contiene una letra más, siendo del formato *AA-000-AA*.



Fig. 4. Evolución de la chapa patente de los automotores en la República Argentina desde 1964 a la actualidad.

Una vez que se generan los datos es posible hacer una estimación real de la antigüedad del parque automotor local. A su vez, puede realizarse la comparativa entre la antigüedad del parque local y lo registrado a nivel nacional, teniendo en cuenta que este estudio se restringe al microcentro de Bahía Blanca.

3 Resultados y discusiones

En esta sección se presentan los resultados obtenidos, tanto globales como segmentados por día de recolección de datos, localización y categorización seleccionadas. Cabe destacar que los resultados presentados se encuentran acotados, es decir, son representativos de dos momentos del año en tres horarios considerados de alta circulación. El fin fue obtener un primer análisis de la cantidad, antigüedad y tipo de vehículo que circula por el microcentro de la ciudad de Bahía Blanca, para avanzar en un futuro cercano con estudios más profundos.

3.1 Cantidad de unidades contabilizados en cada intersección por tipo de vehículo.

Las Figuras 5 y 6 corresponden a la cantidad de unidades de cada tipo de vehículo por intersección monitoreada, en los días y horarios seleccionados. Se puede observar en la Figura 5, correspondiente al 7 de enero de 2020, la gran predominancia del automóvil particular, entre un 60% y un 75% de los vehículos que transitaron por las intersecciones seleccionadas pertenecen a este tipo de unidades. En las esquinas denominadas P1 y P2 se puede ver que el segundo segmento mayoritario son las camionetas o pick ups, con un 10% de representatividad mientras que, en las intersecciones P3 y P4 son las motocicletas con un 14% de presencia. En la Figura 6, correspondiente al 9 de marzo de 2020, también se visualiza la gran predominancia del automóvil sedan (60-75%), seguido de las motocicletas (10-15%) y camionetas (10-12%).

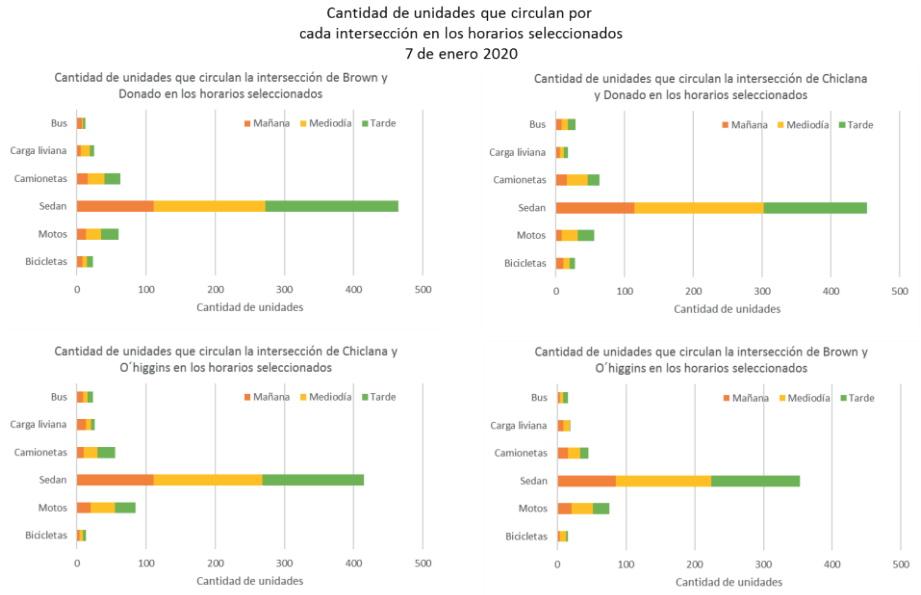

Fig. 5. Cantidad de unidades y tipo de vehículo que circularon por cada intersección seleccionada en los horarios monitoreados el día 7 de enero de 2020.

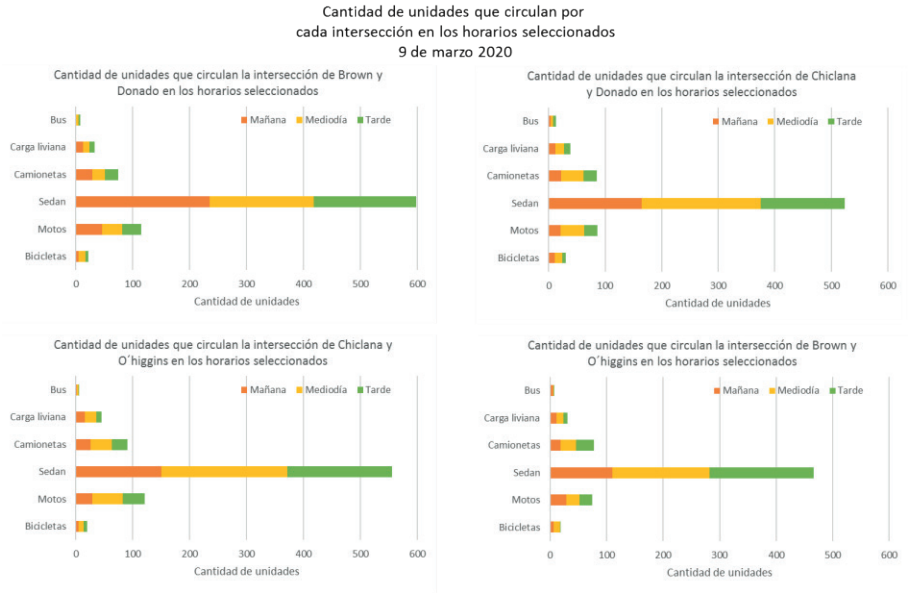

Fig. 6. Cantidad de unidades y tipo de vehículo que circularon por cada intersección seleccionada en los horarios monitoreados el día 9 de marzo de 2020.

De la comparativa entre ambas fechas podemos concluir que la tendencia es la misma en cuanto a porcentaje de cada tipo de vehículo que circula por las intersecciones estudiadas. En cada horario también se observa la misma predominancia. Es por ello, que se concluye que el automóvil particular es el vehículo que más presencia tiene en el tránsito local estudiado. No obstante, se halló una gran diferencia entre ambos periodos estudiados para el flujo vehicular en todas las categorías (Tabla 1). En enero, se obtuvo un promedio diario de 1235 automóviles tipo sedán por hora mientras que para el mes de marzo fue de 1513, lo que resulta en un incremento del 22,5%. Para la categoría motos y camionetas se contabilizó un aumento del 39% en el mes de marzo respecto de enero, mientras que para carga liviana hubo un incremento desde 65 unidades por hora a 104 (60%) para el mes de mayor actividad evaluado.

Tabla 1. Cantidad de unidades por hora promedio que transitan por el microcentro de la ciudad de Bahía Blanca en hora pico, para los meses de enero y marzo (pre-COVID-19) del 2020.

Tipo de vehículo	Cantidad de unidades por hora	
	Enero	Marzo
Sedan	1235	1513
Motos	203	280
Camionetas	166	232
Carga Liviana	65	104

3.2 Análisis de relación entre horarios e intersecciones seleccionadas.

Las Figura 7 y 8 presenta las salidas obtenidas del software InfoStat, en las cuales se muestran los resultados arrojados utilizando el método de comparación de Fisher. En la Figura 7 se visualiza la salida correspondiente al día 7 de enero de 2020 mientras que, en la Figura 8 la del 9 de marzo de 2020.

Del análisis de la salida obtenida para enero se muestra que existe una diferencia significativa entre los horarios y puntos donde se realizaron los videos. En el caso del horario evaluado se puede concluir que en el día de enero hay menos tránsito en horas de la mañana, mientras que no hay diferencias significativas entre el mediodía y la tarde. En cuanto a los sitios observados, se puede analizar que la mayor diferencia se da en el punto P3, mientras que los restantes no muestran diferencias significativas. Por otro lado, de la salida correspondiente al mes de marzo se establece que no existen diferencias significativas entre los horarios e intersecciones seleccionadas.

Análisis de la varianza

Variable	N	R^2	R^2 Aj	CV
Flujo	12	0,93	0,87	7,61

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	364,73	5	72,95	15,15	0,0024
Hora	276,03	2	138,01	28,66	0,0009
Punto	88,71	3	29,57	6,14	0,0293
Error	28,89	6	4,81		
Total	393,62	11			

Test:LSD Fisher Alfa=0,05 DMS=3,79666

Error: 4,8150 gl: 6

Hora	Medias	n	E.E.		
8 am	22,41	4	1,10	A	
7 pm	30,14	4	1,10		B
12 pm	33,93	4	1,10		B

Medias con una letra común no son significativamente diferentes (p > 0,05)

Test:LSD Fisher Alfa=0,05 DMS=4,38400

Error: 4,8150 gl: 6

Punto	Medias	n	E.E.		
3	24,24	3	1,27	A	
1	29,43	3	1,27		B
4	30,50	3	1,27		B
2	31,14	3	1,27		B

Medias con una letra común no son significativamente diferentes (p > 0,05)

Fig. 7. Salida obtenida del software estadístico InfoStat para los datos del día 7 de enero de 2020, ciudad de Bahía Blanca, usando el método de comparación de Fisher.

Análisis de la varianza

Variable	N	R^2	R^2 Aj	CV
Flujo	12	0,41	0,00	14,39

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	111,00	5	22,20	0,84	0,5663
Hora	25,41	2	12,70	0,48	0,6401
Punto	85,59	3	28,53	1,08	0,4259
Error	158,48	6	26,41		
Total	269,48	11			

Test:LSD Fisher Alfa=0,05 DMS=8,89244

Error: 26,4141 gl: 6

Hora	Medias	n	E.E.	
7 pm	34,50	4	2,57	A
8 am	34,87	4	2,57	A
12 pm	37,76	4	2,57	A

Medias con una letra común no son significativamente diferentes (p > 0,05)

Test:LSD Fisher Alfa=0,05 DMS=10,26811

Error: 26,4141 gl: 6

Punto	Medias	n	E.E.	
3	32,73	3	2,97	A
1	33,67	3	2,97	A
4	37,00	3	2,97	A
2	39,43	3	2,97	A

Medias con una letra común no son significativamente diferentes (p > 0,05)

Fig. 8. Salida obtenida del software estadístico InfoStat para los datos del día 9 de marzo de 2020, ciudad de Bahía Blanca, usando el método de comparación de Fisher.

Además, con los datos obtenidos y haciendo uso nuevamente del método de comparación de Fisher se habilita la posibilidad de realizar un estudio entre los dos meses analizados, con el fin de visualizar si existen diferencias significativas entre los distintos horarios considerados (Fig. 9). Del análisis de la salida obtenida por InfoStat se establece que existen diferencias significativas entre los meses en estudio. Además, también se presentan contrastes entre los diferentes horarios contemplados.

Por último, se pueden utilizar los datos para generar una media total del flujo vehicular por minuto en la cuadra del microcentro bahiense analizada, para cada mes contemplado. Se obtuvo un flujo de 28,83 vehículos totales por minuto que transitan el área de estudio seleccionada para el mes de enero mientras que, para marzo la media fue de 35,71. Lo cual significa un incremento del flujo vehicular total del 24% en marzo.

Análisis de la varianza

Variable	N	R^2	R^2 Aj	CV
Flujo	24	0,52	0,45	14,79

Cuadro de Análisis de la Varianza (SC tipo III)

F.V.	SC	gl	CM	F	p-valor
Modelo	491,96	3	163,99	7,20	0,0018
Hora	207,68	2	103,84	4,56	0,0234
Mes	284,28	1	284,28	12,48	0,0021
Error	455,42	20	22,77		
Total	947,39	23			

Test:LSD Fisher Alfa=0,05 DMS=4,97702

Error: 22,7712 gl: 20

Hora	Medias	n	E.E.		
8 am	28,64	8	1,69	A	
7 pm	32,32	8	1,69	A	B
12 pm	35,84	8	1,69		B

Medias con una letra común no son significativamente diferentes (p > 0,05)

Test:LSD Fisher Alfa=0,05 DMS=4,06372

Error: 22,7712 gl: 20

Mes	Medias	n	E.E.		
Enero	28,83	12	1,38	A	
Marzo	35,71	12	1,38		B

Medias con una letra común no son significativamente diferentes (p > 0,05)

Fig. 9. Salida obtenida del software estadístico InfoStat para todos los datos recolectados usando el método de comparación de Fisher, con el fin de comparar el flujo total en los horarios analizados para los dos meses en estudio.

3.3 Antigüedad de la flota vehicular analizada mediante la clasificación según chapa patente.

Se generó la segmentación de la flota vehicular local según el tipo de chapa patente, con el fin de presentar el análisis de la antigüedad del parque automotor de la ciudad. Para realizar este análisis se agruparon todos los datos recolectados en ambos días y en los diferentes horarios, obteniendo de esta manera una visión más global de la edad de los vehículos que transitan por los puntos seleccionados del microcentro de la ciudad de Bahía Blanca. En la Tabla 2 se presentan la cantidad de vehículos que comprenden cada segmento etario, según el recuento realizado mediante la observación de las filmaciones generadas.

Del análisis de la Tabla 2 se obtiene que el 25% de los vehículos observados que transitaron por el microcentro de la ciudad en los días y horarios seleccionados tienen menos de 4 años de antigüedad; un 71% tienen entre 4 y 20 años, restando solo un 4% para aquellas unidades mayores a 20 años.

Tabla 2. Cantidad de vehículos por tipo y antigüedad. Se contemplaron todas las unidades que registraron su paso por los puntos monitoreados –P1, P2, P3 y P4– para ambas épocas en evaluación –enero y marzo 2020–.

Tipo de vehículo	Antigüedad	Cantidad de unidades
Sedan	Menor a 4 años	895
	Entre 4 y 20 años	2809
	Mayor a 20 años	122
Pick up	Menor a 4 años	198
	Entre 4 y 20 años	327
	Mayor a 20 años	36
Carga Liviana	Menor a 4 años	57
	Entre 4 y 20 años	103
	Mayor a 20 años	8
Bus	Menor a 4 años	23
	Entre 4 y 20 años	158
	Mayor a 20 años	0

Si se realiza una comparativa entre los resultados obtenidos de antigüedad y la media nacional registrada según la Asociación de Fábricas Argentinas de Componentes (AFAC) [21], se obtiene la Figura 10. En la misma se puede visualizar que, según los datos muestreados, el parque automotor local que transita el microcentro de la ciudad de Bahía Blanca es un 17% más nuevo en comparación con la media nacional. Este resultado es coherente con lo reportado por Grassi et al [22].

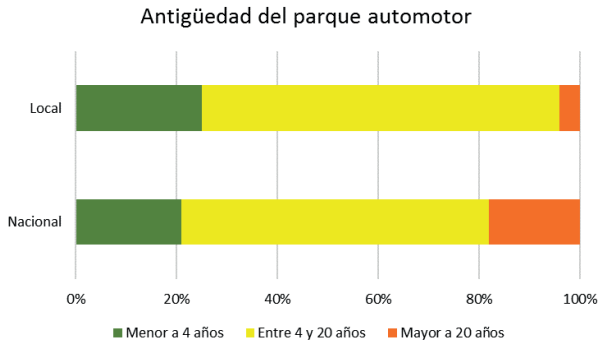

Fig. 10. Comparativa entre la antigüedad de la flota vehicular nacional y la local.

4 Conclusiones

El estudio del flujo vehicular y su categorización, realizado en la ciudad de Bahía Blanca en determinados puntos seleccionados del microcentro en enero y marzo de 2020, nos permite concluir que el vehículo con mayor predominancia en circulación es

el denominado sedan o automóvil particular. Por otro lado, pudo determinarse que en el mes de enero se encuentran algunas diferencias significativas entre los horarios e intersecciones seleccionadas, mientras que en el mes de marzo no se observan estas diferencias. Esto es coherente con el tipo de actividad de época estival de vacaciones (mes de enero) y los movimientos normales del inicio de clases (mes de marzo pre-COVID-19). En cuanto a la antigüedad del parque automotor de la ciudad se pudo determinar que el mismo es un 17% más nuevo que el reportado a nivel nacional.

La ciudad de Bahía Blanca se perfila desde la esfera gubernamental como una ciudad tendiente a convertirse en una ciudad inteligente. Para ello, el análisis del flujo vehicular exhibido en este trabajo sirve como puntapié para la implementación de una gestión inteligente del tráfico. Si en un futuro se involucraran herramientas de análisis, simulación, optimización y predicción capaces de medir el flujo vehicular se podría conseguir un volumen de datos que se usará en la implementación de modificaciones del tránsito vehicular, la semaforización y las emisiones de contaminantes. De esta manera la ciudad de Bahía Blanca se convertiría en una más agradable para vivir y transitar tanto vehicular como peatonalmente.

Lo presentado en este trabajo forma parte de un estudio mucho más amplio, de modo que se tiene previsto continuar con las filmaciones, en más momentos del año y hacerlo extensivo a otras localizaciones de la ciudad de Bahía Blanca. Si bien resulta dificultoso realizar estas tareas de modo manual, su importancia justifica el esfuerzo ya que este estudio debería ser realizado de manera permanente, con el objetivo de generar datos sobre la evolución del parque automotor local.

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Inventario de Emisiones de la Aviación Civil, Navegación Marítima y Ferrocarriles de la ciudad de Bahía Blanca para el año 2018.

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Resumen. La ciudad de Bahía Blanca cuenta con uno de los puertos más importantes de Argentina, así como también con gran cantidad de conexiones ferroviarias que atraviesan el ejido urbano. Por otro lado, la aeroestación civil Comandante Espora también forma parte de la ciudad, en la cual aterrizan y despegan, principalmente, vuelos comerciales de cabotaje. Tanto el transporte marítimo, como el ferroviario y aéreo son considerados fuentes móviles no carreteras de emisión de contaminantes y gases de efecto invernadero. La mayoría del transporte no carretero funciona utilizando combustible Diesel, es por ello que son considerados productores de gran cantidad de emisiones de NO_x, entre otros gases, y deben ser incluidos en los análisis preliminares de contaminación de las ciudades. Cabe destacar que un inventario de emisiones preciso y actualizado sobre el transporte no carretero es esencial, dado que, permite disponer de información confiable con el fin de ser utilizada en la mejora de las políticas de calidad de aire. Por lo tanto, el presente trabajo muestra los resultados obtenidos de la confección del inventario de emisiones del transporte no carretero de la ciudad de Bahía Blanca para el año 2018. Además, se realiza una comparativa con datos existentes del año 2013 para el tipo de transporte en estudio, concluyendo que todas las emisiones disminuyen en 2018, en concordancia con la caída de la actividad económica.

Palabras claves: Inventario de emisiones, Bahía Blanca, Transporte no carretero.

1 Introducción

Un inventario de emisiones contabiliza los gases emitidos a la atmósfera durante un período de tiempo determinado -en general un año calendario- para un territorio determinado. Es por ello que debe definirse, como punto de partida, el tipo de fuente que se va a considerar en el estudio y los contaminantes que se desean estimar [1, 2].

El caso de estudio presentado corresponde a la ciudad de Bahía Blanca para el año 2018. La urbe se encuentra emplazada al sudoeste de la provincia de Buenos Aires, Argentina, considerándose un punto estratégico que permite una relación mercantil estrecha con el centro y el sur de la región pampeana y el norte de la Patagonia, mediante múltiples conexiones viales y ferroviarias. Cuenta con un importante puerto que constituye la vinculación de la ciudad con el exterior ya que, posibilita un fluido intercambio comercial con el resto del mundo y lo convierte en la principal estación marítima de aguas profundas de la Argentina. El transporte ferroviario se encarga prioritariamente del traslado de cereales al puerto local y de productos petroquímicos con origen en la ciudad y con destino en la Ciudad Autónoma de Buenos Aires. Por otro lado, la ciudad cuenta con la aerostación civil Comandante Espora en donde operan diferentes empresas aéreas que realizan vuelos de cabotaje [3].

Dado que, la ciudad posee toda la mencionada infraestructura de transporte no carretero es de importancia mantener un inventario de emisiones actualizado. El transporte carretero como ser, automotores, camiones, etc., ha sido reconocido como una importante fuente móvil de contaminación atmosférica mientras que se le ha prestado menor atención al control de las emisiones provenientes de fuentes móviles no carreteras [4]. Nuestra línea de investigación ha contemplado ambos tipos de fuentes móviles, es por ello que en este trabajo se presentan los datos para el transporte no carretero, y pueden encontrarse los resultados obtenidos para el sector carretero en Grassi et. al. [5].

La elaboración del presente inventario de emisiones de los segmentos no carreteros contempla el transporte aéreo, marítimo y ferroviario de la ciudad de Bahía Blanca para el año 2018. Cabe destacar que un inventario de emisiones con estimaciones precisas es esencial para mejorar las políticas sobre calidad de aire. La precisión estará dada por la disponibilidad de información sobre cantidad de operaciones de cada rubro analizado, nivel de actividad y factores de emisión [6]. Para la confección se recolectó gran cantidad de información, la cual fue recopilada de fuentes bibliográficas y de las estadísticas anuales de las diferentes entidades representativas de cada tipo de transporte. Se siguieron los lineamientos del Panel Intergubernamental para el Cambio Climático (IPCC, por sus siglas en inglés) [1], así como también se consultó el Inventario Nacional de Gases de Efecto Invernadero (GEIs) de la República Argentina [2]. Cabe destacar que también se tuvo en consideración un antecedente de inventario de emisiones para la ciudad de Bahía Blanca que data del año 2013 [7], el cual fue confeccionado por un ente gubernamental que tiene a su cargo el control y monitoreo de las industrias de la ciudad y servirá para realizar una comparativa entre los dos años.

La falta de datos actualizados y fidedignos no permite tener regulaciones claras y controles fuertes sobre las emisiones de fuentes móviles no carreteras [8]. Es por ello que el objetivo de este trabajo es generar datos confiables y actualizados sobre la estimación de las emisiones generadas por este tipo de fuentes móviles de nuestra ciudad. Para esto, se evaluaron los aportes de diversos contaminantes atmosféricos y precursores, entre los que se encuentran: monóxido de carbono (CO), dióxido de azufre (SO_2), óxidos de nitrógeno (NO_x) y compuestos orgánicos volátiles distintos al metano (COVNM). Adicionalmente, se evaluaron las emisiones de dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O), considerados GEIs. El presente inventario de emisiones de fuentes móviles no carreteras constituye una herramienta para el análisis de

emisiones históricas y futuras, que resultan de utilidad en la toma de decisiones respecto a las políticas gubernamentales y su impacto.

2 Metodología y recolección de datos

Para realizar el cálculo de las emisiones de contaminantes generadas por las fuentes seleccionadas, se utilizó la metodología de factores de emisión (FEs). Un FE es un valor representativo que trata de relacionar la cantidad de un contaminante emitido a la atmósfera con una actividad asociada con dicha liberación. Estos factores se expresan como el peso del contaminante por unidad de peso, volumen, distancia, o duración de la actividad de emisión (por ejemplo, gramos de CO emitido por litro de combustible consumido por un automóvil). Éstos facilitan la estimación de las emisiones de diversas categorías de fuentes de contaminación del aire (una categoría de fuente es un sector específico de la industria o grupo de fuentes de emisión similares). En la mayoría de los casos, estos factores de emisión son simplemente promedios de todos los datos disponibles o se han desarrollado y compilado a partir de datos de prueba en las fuentes de origen, estudios de balance de materiales y/o estimaciones de ingeniería [9].
Utilizamos un procedimiento similar al presentado por el IPCC, el cual está disponible en el documento "Directrices del IPCC de 2006 para los Inventarios Nacionales de Gases de Efecto Invernadero" [10]. La ecuación general utilizada en un inventario de emisiones se define como número (1). Donde *E* corresponde a la tasa de emisión, expresada en unidades de masa por unidad de tiempo; *A* a la tasa de actividad, y *FE* al factor de emisión, expresado en masa de contaminante emitido por unidad de actividad.

$$E = A * FE \tag{1}$$

La tasa de actividad (A) seleccionada para este estudio es el volumen de combustible consumido anualmente [m^3/(año)] por cada categoría de transporte y tipo de vehículo establecida. En cuanto a los factores de emisión usados para los casos de transporte ferroviario, marítimo y aéreo se emplearon los que propone el Inventario Nacional de Emisiones de GEIs [2]. Allí se pueden encontrar los FEs para todos los contaminantes estudiados: monóxido de carbono (CO), dióxido de azufre (SO_2), óxidos de nitrógeno (NO_x) y compuestos orgánicos volátiles distintos al metano (COVNM), así como para los GEIs estudiados: dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O). Para trabajar con los FEs seleccionados se debió realizar un correcto pasaje de unidades, recurriendo a la información del Poder Calorífico Inferior (PCI) del combustible, extraído de tablas de la página web de la Secretaría de Energía de la Nación [11], y a la densidad del combustible determinada a 15 ºC según norma ASTM D - 1298/4052, extraídos de las fichas técnicas de YPF [12, 13, 14]. Los datos propios de cada tipo de transporte fueron obtenidos de las estadísticas anuales para el 2018 de cada ente representativo del rubro. Además, fueron usados diversos datos extraídos del Inventario de Emisiones Gaseosas de Fuentes Móviles – Bahía Blanca, 2013 [7]. En los siguientes apartados se presentan los datos y metodologías seguidas para cada tipo de transporte considerado.

Por último, dado que existe un inventario de emisiones del transporte no carretero de la ciudad de Bahía Blanca para el año 2013, el cual fue considerado como base de referencia para el presente estudio, se procedió a realizar una comparación contra los resultados obtenidos para el 2018. Para ello se realizó una unificación en el uso de los factores de emisión, considerando para ambos años los presentados en este trabajo.

2.1 Transporte aéreo

En esta sección se presentan los datos relacionados con las operaciones aéreas de la aeroestación civil "Comandante Espora" de Bahía Blanca, considerando solo aquellas operaciones comerciales regulares las cuales son las que están sujetas a itinerario y horario prefijado. Se detalla el número de operaciones que tuvieron lugar a lo largo del año 2018 y los datos de actividad relacionados con el consumo de combustible.

Del Anuario Estadístico 2018 [15] de la Administración Nacional de Aviación Civil Argentina se obtuvo un resumen de las operaciones aéreas comerciales realizadas en Bahía Blanca durante el año 2018. Para hacer la clasificación por tipo de aeronave se consideró que los aviones comerciales que llegan al aeropuerto corresponden a: los Embraer ERJ-190 y los Boeing 737-700 y 737-800. Según datos recolectados de la página web oficial del aeropuerto local [16], se llega a la conclusión que el 66% de los vuelos corresponden a los Embraer ERJ-190, un 26% a los Boeing 737-800 y 8% restante a los Boeing 737-700. Siguiendo con la clasificación que fue utilizada en el Inventario de Emisiones Gaseosas de Fuentes Móviles – Bahía Blanca, 2013 [7], podemos considerar a los Embraer ERJ-190 como aeronaves medianas, mientras que los Boeing serán considerados aeronaves pesadas. La cantidad de operaciones comerciales por tipo de aeronave se presenta en la Tabla 1.

Tabla 1. Cantidad de operaciones por cada tipo de aeronave durante el año 2018 en la aeroestación de Bahía Blanca.

Tipo de aeronave	Cantidad de operaciones
Aeronaves Pesadas	1769
Aeronaves Medianas	3435

Es necesario aclarar que el consumo de combustible "operativo" de una aeronave se corresponde con lo reportado por el IPCC como consumo por LTO (landing-take off), y el consumo por "rodaje" es debido al modo crucero [17]. En la Tabla 2 se presentan los datos de actividad para cada tipo de aeronave, que fueron extraídos del Inventario de Emisiones Gaseosas de Fuentes Móviles – Bahía Blanca, 2013 [7]. Luego, en la Tabla 3, se muestran los resultados del consumo total de combustible, mientras que los FEs correspondientes a la aviación comercial son enumerados en las Tablas 4 y 5.

Tabla 2. Combustible consumido en cada operación tanto en rodaje como en estado operativo por tipo de aeronave, expresada en [m^3/operación], para Bahía Banca, año 2018.

Tipo de aeronave	Consumo Operativo [m^3/operación]	Consumo en Rodaje [m^3/operación]
Aeronaves Pesadas	0,85	0,13
Aeronaves Medianas	0,45	0,07

Tabla 3. Combustible consumido anualmente por tipo de aeronave tanto en rodaje como en estado operativo, expresado en [m^3/año], para Bahía Banca, año 2018.

Tipo de aeronave	Consumo Operativo [m^3/año]	Consumo en Rodaje [m^3/año]	Consumo Total [m^3/año]
Aeronaves Pesadas	1503,96	230,02	1733,97
Aeronaves Medianas	1545,59	240,42	1786,01
TOTAL	3049,55	470,44	3519,98

Tabla 4. FEs de contaminantes basados en el tipo de combustible consumido por el transporte aéreo [kg de contaminante emitido/m^3 de combustible consumido].

Tipo de combustible	CO	NO_x	SO_2	COVNM
Aerokerosene	3,52	8,82	1,60	1,76

Tabla 5. FEs de gases de efecto invernadero basados en el consumo de combustible del transporte aéreo [kg de GEI emitido/m^3 de combustible consumido].

Tipo de combustible	CO_2	CH_4	N_2O
Aerokerosene	2522,52	0,018	0,071

Como parte de la metodología usada para el cálculo de las estimaciones de emisiones por parte del transporte aéreo se utilizó la ecuación 3.6.1 que se presenta en las "Directrices del IPCC de 2006 para los Inventarios Nacionales de GEIs" [17], la cual es mostrada en este trabajo como número (2).

$$E = Consumo\ de\ Combustible * FE \quad (2)$$

2.2 Transporte marítimo

En el presente apartado se consideran las entradas y salidas del puerto de aquellos buques de gran porte, la flota pesquera y remolcadores. En el caso de buques de gran porte (de navegación), se considera para el cálculo, el combustible consumido para la navegación en un trayecto de 10 km de entrada y 10 km de salida del puerto, más el consumo de combustible empleado en servicios durante la espera y estadía.

Los datos de cantidad de buques de navegación fueron extraídos de las estadísticas del Consorcio de Gestión del Puerto de Bahía Blanca (CGPBB) [18]. En el caso de pesqueros y remolcadores se mantuvo la misma cantidad que la utilizada en el Inventario de Emisiones Gaseosas de Fuentes Móviles – Bahía Blanca, 2013 [7], dado que este dato no se encuentra en las estadísticas mencionadas y no recibimos respuesta a las consultas sobre este dato (Tabla 6).

Tabla 6. Cantidad de embarcaciones, por tipo, durante el año 2018 en el Puerto de Bahía Blanca.

Tipo de embarcación	Cantidad
Buques de Navegación	644
Flota de Remolcadores y Pesqueros	23*

* dato tomado del año 2013

Los datos de actividad de ambas categorías fueron extraídos del Inventario de Emisiones Gaseosas de Fuentes Móviles – Bahía Blanca, 2013 [7], los mismos se presentan, de manera resumida y ordenada, en las Tablas 7, 8 y 9. Se consideró que el consumo promedio de fuel-oil para buques de gran porte es de 25 t/día, a una velocidad de 22,2 km/h. Los cálculos de consumo de combustible se realizan en base a los 20 kilómetros recorridos en entrada y salida del puerto. Además, el consumo de gas-oil empleado en servicios para los buques de navegación es de aproximadamente de 3 t/día, considerando un tiempo de espera y estadía en el puerto de 2,5 días. En el caso de la flota pesquera y de remolcadores, el consumo de gas-oil es de 200 litros/semana y se considera que el tiempo de actividad es de 48 semanas al año (4 horas por día durante los 365 días del año). Finalmente, los FEs correspondientes al transporte marítimo son enumerados en las Tablas 10 y 11.

Tabla 7. Combustible consumido por buques durante navegación, [m^3/año], para Bahía Banca, año 2018.

Tipo de Embarcación	Combustible utilizado	Embarcaciones al año	Actividad [km]	Consumo [m^3/km]	Consumo [m^3/año]
Buques de Navegación	Fuel-Oil	644	20	0,048	618,24

Tabla 8. Combustible consumido por buques durante su estadía para servicios, [m^3/año], para Bahía Banca, año 2018.

Tipo de Embarcación	Combustible utilizado	Embarcaciones al año	Estadía [días]	Consumo [m^3/día]	Consumo [m^3/año]
Buques de Navegación	Gas-Oil	644	2,5	3,41	5490,10

Tabla 9. Combustible consumido por la flota pesquera y remolcadores, [m^3/año], para Bahía Banca, año 2018.

Tipo de Embarcación	Combustible utilizado	Embarcaciones al año	Actividad [semanas]	Consumo [m^3/semana]	Consumo [m^3/año]
Pesqueros y Remolcadores	Gas-Oil	23	48	0,20	220,80

Tabla 10. FEs de contaminantes basados en el tipo de combustible consumido por el transporte marítimo [kg de contaminante emitido/m^3 de combustible consumido].

Tipo de combustible	CO	NO_x	SO_2	COVNM
Fuel – Oil	39,59	59,38	7,84	7,91
Gas – Oil	36,55	54,82	1,32	7,31

Tabla 11. FEs de gases de efecto invernadero basados en el tipo de combustible consumido por el transporte marítimo [kg de GEI emitido/m^3 de combustible consumido].

Tipo de combustible	CO_2	CH_4	N_2O
Fuel – Oil	3064,42	0,27	0,079
Gas – Oil	2708,35	0,25	0,073

La metodología usada para el cálculo de las estimaciones de emisiones por parte del transporte marítimo sigue la ecuación 3.5.1 que se presenta en las "Directrices del IPCC de 2006 para los Inventarios Nacionales de GEIs" [17], la cual es mostrada en este trabajo como número (3). Donde *a* se relaciona con el tipo de combustible consumido y *b* con el tipo de embarcación considerada.

$$E = \sum Consumo\ de\ Combustible_{a,b} * FE_{a,b} \quad (3)$$

2.3 Transporte ferroviario

Dentro de este segmento se tuvieron en cuenta los trenes de transporte de carga y de pasajeros, que circulan en un radio de 10 km de la ciudad. La información recolectada contabiliza arribos, partidas y maniobras de operaciones. Se trabajó con los datos actualizados del año 2018, para los trenes de carga y las locomotoras de maniobra. Mientras que, para los trenes de pasajeros se considera la noticia emitida por uno de los diarios locales en marzo de 2019 [19], en donde se menciona la cantidad de pasajeros y formaciones que transitan semanalmente por la ciudad. En las Tablas 12 y 13 se presentan los datos de actividad recolectados, cantidad de operaciones anuales y tiempo de funcionamiento de las locomotoras de maniobra, junto a los respectivos consumos de combustible. Además, los FEs correspondientes al transporte ferroviario son enumerados en las Tablas 14 y 15.

Tabla 12. Combustible consumido en arribos y partidas de trenes de carga y pasajeros, [m^3/año], para Bahía Banca, año 2018.

Tipo de formación	Combustible utilizado	Formaciones al año	Consumo [m^3/operación]	Consumo [m^3/año]
Tren de carga	Gas - Oil	4055	0,05	202,75
Tren de pasajeros	Gas - Oil	313	0,03	9,39

Tabla 13. Combustible consumido por locomotoras de maniobra, [m^3/año], para Bahía Banca, año 2018.

Tipo de formación	Combustible utilizado	Tiempo de funcionamiento [horas]	Consumo [m^3/hora]	Consumo [m^3/año]
Locomotora de maniobra	Gas - Oil	16506	0,013	214,58

Tabla 14. FEs de contaminantes basados en el tipo de combustible consumido por el transporte ferroviario [kg de contaminante emitido/m^3 de combustible consumido].

Tipo de combustible	CO	NO_x	SO_2	COVNM
Gas – Oil	36,55	43,86	1,32	7,31

Tabla 15. FEs de gases de efecto invernadero basados en el tipo de combustible consumido por el transporte ferroviario [kg de GEI emitido/m^3 de combustible consumido].

Tipo de combustible	CO_2	CH_4	N_2O
Gas – Oil	2708,35	0,15	1,04

Para el transporte ferroviario se seleccionó la ecuación 3.4.1 que se presenta en las "Directrices del IPCC de 2006 para los Inventarios Nacionales de GEIs" [17], la cual es presentada a continuación con el número (4). Donde j se relaciona con el tipo de combustible consumido.

$$E = \sum Consumo\ de\ Combustible_j * FE_j \quad (4)$$

3 Resultados y discusiones

Luego de realizar los cálculos correspondientes, según las metodologías presentadas previamente, se presenta en la tabla 16 el resumen de todos los resultados obtenidos por tipo de transporte y compuesto gaseoso estudiado. También se muestran los resultados de las emisiones anuales de cada contaminante (Fig. 1) y de cada gas de efecto invernadero (Fig. 2) en forma gráfica para todos los tipos de transportes.

De los resultados obtenidos puede observarse que el mayor porcentaje de gases contaminantes, en las categorías de transporte seleccionadas, corresponden a los NO_x con

un 54,33%. Seguido de las emisiones de CO (35,52%), COVNM (7,61%) y por último los SO_2 (2,53%). En cuanto a gases de efecto invernadero son predominantes las emisiones de CO_2 (99,99%). Por otro lado, se evidencia que el transporte marítimo genera el mayor aporte de todos los gases contaminantes (CO, NO_x, COVNM y SO_2) y también de los gases de efecto invernadero: CO_2 y CH_4, mientras que el ferroviario generó mayor cantidad de emisiones de N_2O para la ciudad de Bahía Blanca durante el año de estudio 2018. Esto se debe a que el transporte marítimo es el que, según lo reportado, consume mayor cantidad de combustible. Si bien la mayor proporción viene dada por el gas-oil, cabe destacar que los buques suelen quemar combustibles más pesados, como el fuel-oil, en sus motores de propulsión [4]. Es por ello que no sorprende que el transporte marítimo sea el que más aporte de emisiones genere, y que más aún las emisiones de NO_x sean las más predominantes como se ha reportado en otros lugares del mundo [20, 21, 22]. Dado que estamos analizando la contribución que tienen los diferentes tipos de transporte no carretero en la ciudad de Bahía Blanca debemos recordar que no consideramos, por ejemplo, las emisiones que los buques realizan en alta mar, sino las generadas en un pequeño recorrido de ingreso y egreso al puerto, además de la estadía en el mismo. Mas aún, debido a que la estadía se estima como 2,5 días en promedio, esta representa la mayor cantidad de emisiones.

Dado que existe un antecedente previo en la ciudad de inventario de emisiones para transporte no carretero, el cual fue considerado como base de referencia para el presente estudio, se presentan en las Figuras 3 y 4 la comparativa entre el año 2013 y el 2018 de manera gráfica mientras que, la tabla 17 contiene los resultados numéricos.

Tabla 16. Resultados finales obtenidos de emisiones de contaminantes y GEIs por tipo de transporte en la ciudad de Bahía Blanca, para el año 2018, en [t/año].

Gas contaminante o GEI	Transporte Aéreo	Transporte Marítimo	Transporte Ferroviario
CO	12,42	233,21	15,72
NO_x	31,05	349,82	18,86
COVNM	6,21	46,64	3,14
SO_2	5,63	12,42	0,57
CO_2	8.879,23	17.361,69	1164,54
CH_4	0,06	1,63	0,07
N_2O	0,25	0,47	0,45

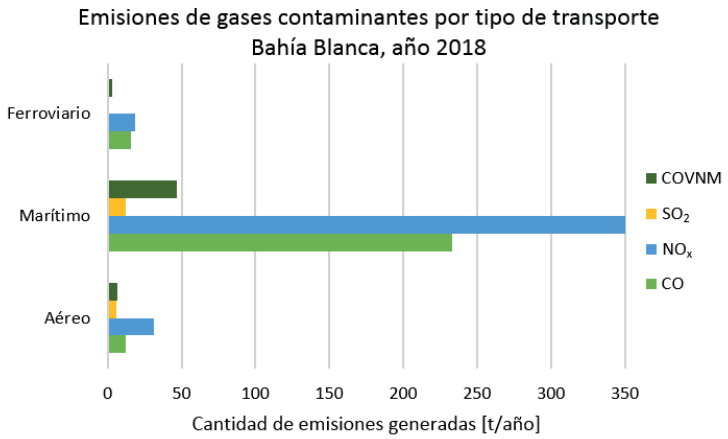

Fig. 1. Cantidad de emisiones de gases contaminantes generadas por tipo de transporte en la ciudad de Bahía Blanca, para el año 2018, en [t/año].

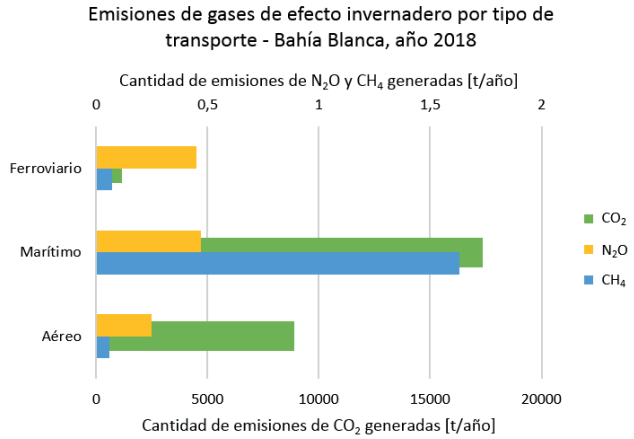

Fig. 2. Cantidad de emisiones de gases de efecto invernadero generadas por tipo de transporte en la ciudad de Bahía Blanca, para el año 2018, en [t/año].

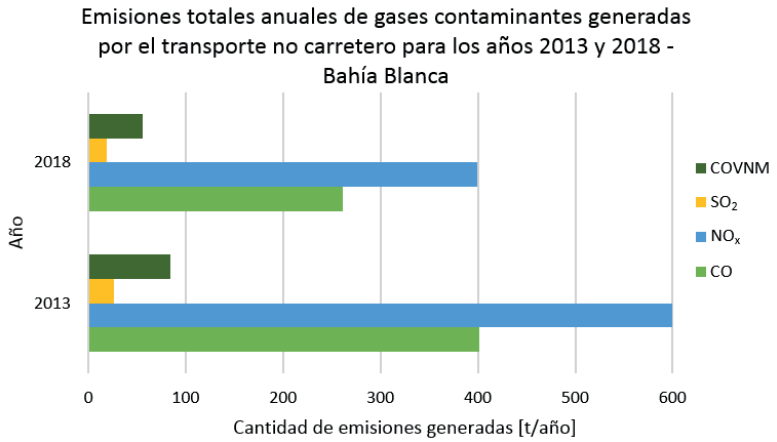

Fig. 3. Cantidad de emisiones totales anuales de los gases contaminantes estudiados para los años 2013 y 2018, englobando los tres tipos de transporte analizados en la ciudad de Bahía Blanca, en [t/año].

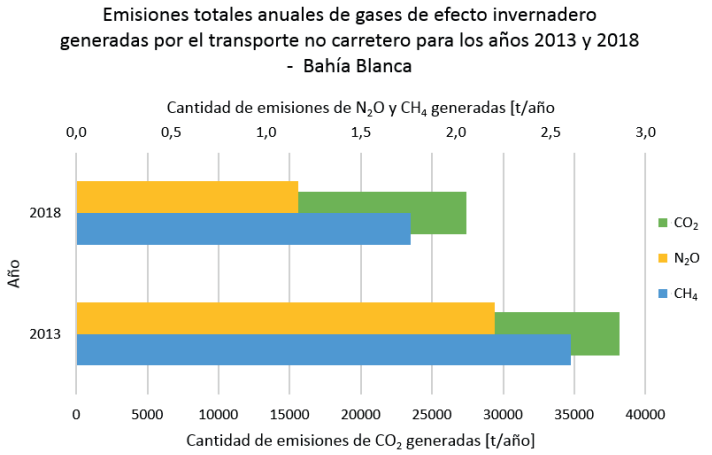

Fig. 4. Cantidad de emisiones totales anuales de los gases de efecto invernadero estudiados para los años 2013 y 2018, englobando los tres tipos de transporte analizados en la ciudad de Bahía Blanca, en [t/año].

Tabla 17. Resultados de emisiones totales de contaminantes y GEIs del segmento de transporte no carretero de la ciudad de Bahía Blanca, para los años 2013 y 2018, en [t/año].

Gas contaminante o GEI	2013	2018
CO	401,84	261,35
NO_x	599,50	399,73
COVNM	84,22	55,99
SO_2	25,93	18,62
CO_2	38163,21	27405,46
CH_4	2,60	1,76
N_2O	2,21	1,17

Cabe recordar que con el fin de llevar adelante las comparativas entre los años 2013 y 2018 se utilizaron los mismos factores de emisión para ambos periodos, con lo cual las diferencias que se presentan en los resultados están estrechamente relacionadas con los niveles de actividad y no así, con el mejoramiento tecnológico del transporte ni el combustible que se emplea. Del análisis de las gráficas comparativas entre los años 2013 y 2018 (Fig. 3 y 4) se puede ver como las emisiones de gases contaminantes y GEIs han disminuido. Las mismas se han reducido entre un 28% y un 47% (Tabla 17). Esto se debe a que han mermado todas las operaciones marítimas, ferroviarias y aéreas en la ciudad de Bahía Blanca. Tal es así que en 2013 operaron 961 buques, 5678 aviones y 9309 trenes mientras que, en 2018 se redujeron un 33% la cantidad de maniobras en el puerto, un 8,5% las operaciones en la aeroestación y 53% los movimientos de formaciones ferroviarias (Tabla 18). Esto se relaciona estrechamente con los niveles de actividad económica de la ciudad, la región y el país. Si bien se considera que el año 2013 presentó una situación de estancamiento con algunos indicios de mejoría tras la caída del nivel de actividad del 2012, 2013 fue un año en el cual la producción agrícola se ubicó por encima de los niveles promedio históricos [23, 24]. En cuanto al año 2018 se puede decir que, tanto a nivel local como nacional, ha sido un año complejo desde el punto de vista económico. Con un inicio alentador del año que terminó concluyendo en una profunda crisis económica interna para finales del 2018, lo cual se vio reflejado en "una recesión sin precedentes", según la fuente de información del Centro Regional de Estudios Económicos de Bahía Blanca Argentina (CREEBBA) [25]. Por otro lado, utilizando los datos de la serie histórica del Estimador Mensual de Actividad Económica (EMAE) reportados por el Instituto Nacional de Estadísticas y Censos (INDEC) [26], se concluye que la actividad económica del año 2018 cayó respecto del 2013 un promedio del 1,8%. Esto se ve reflejado en la merma de las operaciones del transporte local no carretero provocando una disminución en las emisiones de gases contaminantes y GEIs que reportamos en el presente trabajo.

Tabla 18. Cantidad de operaciones anuales registradas por tipo de transporte no carretero analizado para los años 2013 y 2018, Bahía Banca.

Tipo de transporte	Año	
	2013	2018
Aéreo	5678	5204
Marítimo	961	644
Ferroviario	9309	4368

4 Conclusiones

Durante el 2018 de los tipos de transporte considerados en este estudio, el sector marítimo es el de mayor generación de emisiones de gases contaminantes y de efecto invernadero en la ciudad de Bahía Blanca.

En cuanto a la comparativa entre lo reportado en 2013 y lo obtenido para 2018 se observa, que en este último periodo analizado las emisiones han sido menores, lo cual se corresponde con la disminución de cantidad de operaciones en los tres rubros investigados. Esto último puede relacionarse directamente con la caída de la actividad económica a nivel local, regional y nacional.

Cabe destacar que un inventario de emisiones preciso y actualizado sobre el transporte no carretero es esencial, dado que, permite disponer de información confiable con el fin de ser utilizada en la mejora de las políticas de calidad de aire, sumado al correspondiente estudio de transporte carretero. Este trabajo se enmarca dentro de una línea de investigación sobre contaminación atmosférica debida a fuentes móviles en la ciudad de Bahía Blanca.

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Minimizing the Bullwhip Effect by Forecasting Supply Chain Demand: Case Study of the Argentine Automotive Sector

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Summary: This article studies the uncertainty caused by the Bullwhip effect in the supply chain. The supply chain evaluated in this study is made up of a manufacturer, a distributor, and a retailer, and we studied the effect of demand between the links in the supply chain. The research uses data from the demand for Argentine automotive parts for 48 months and compares the forecast using the Holt-Winters and ARIMA methods over 4 years to minimize the Bullwhip effect.

Key Words: Bullwhip effect, Supply chain, ARIMA models, Time Series, Holt-Winters Method, Automotive Industry.

Introduction

Global markets require modern logistics chains to improve productivity and sustainable growth of international trade. In the same sense, each of the different actors in the supply chain must be coordinated to guarantee good customer service, ensuring a balance between the demand and supply chain. A simple supply chain is made up of independent organizations such as manufacturers, distributors, and retailers [1,2]. The efficiency of the supply chain can be evaluated using the total cost of services [3], the average inventory [4], and the bullwhip effect [5].

The bullwhip effect can be caused by several factors, including; demand forecast, lot order, price fluctuation, rationing measures, and shortages [6]; waiting times [7,8,9], inventory policies [10,11]; replacement policies [12,13,14]; poor control systems [15]; the number of participants in the supply chain [16]; distortion of information in the supply chain [17,18,19,20,21]; company processes [22]; capacity limits [16]; erroneous feedback perception [22]; lack of synchronization in the chain [23]; local optimization without global vision [22]; multiplier effect [15]. Also, the whip effect can be affected by members of the supply chain due to the delay of decision-

making, lack of learning and/or training, and for fear of having an empty stock [24,25,26]. Other aspects have been reported by [27].

The bullwhip effect is a phenomenon that makes administrative management of the supply chain difficult; This effect generates a growing distortion of the demand transmitted by the different agents participating in the flow management of tailor-made products from the market to the producer. In other words, the Bullwhip effect reflects increased uncertainty as orders are transmitted upstream in the supply chain; It is an amplification phenomenon of the demand between the different elements that make up a supply chain.

This article evaluates the impact that the Bullwhip effect has on a supply chain made up of a manufacturer, distributor, and retailer: specifically studying the uncertainty caused by the manufacturer due to the demand variability in each market retailer.

1.1 Demand Forecast

The whip effect makes operational management of the supply chain difficult, in particular, forecasting demand. There are several methods to determine the demand forecast transmitted from the customer to the producer. The various forecasting methods existing in the literature can be classified into the following categories:

- **Time series forecasting techniques**
- **Automatic learning models.**
- **Agent based models**
- **Control engineering models**

The time series forecasting techniques are the moving average (MA), exponential smoothing (ES), auto-regression (AR), and auto-regressive moving average (ARIMA) [28, 29, 30, 31]. These techniques minimize total cost by optimizing the optimal inventory level and the number of orders. We conducted a comparative demand forecast study using the Holt-Winters and ARIMA methods to reduce uncertainty in the supply chain.

2 Methods

Forecasting of the demand time series will be approached using the Holt-Winters method by the seasonal characteristics and the systematic component of the demand. The implementation of the Holt-Winters method is:

For the systematic component of demand [(level + trend) x seasonal factor] with periodicity p of the data. L0, T0, and seasonal factors (S1, S2,… Sp) are obtained using the static forecasting procedure. For period t, the forecast for future periods is given by:

$$F_t+1 = (L_t+T_t)(S_t+1) \text{ y } F_t+n = (L_t + nT_t)S_t+n \quad (1)$$

After observing the demand for period t + 1, the estimates for the level, trend, and seasonal factors expressed in equations (2 - 4) were revised:

$$T_t+1 = \beta(L_t+1 - L_t) + (1- \beta)T \quad (2)$$

$$L_t+1 = \alpha(D_t+1/S_t+1) + (1- \alpha)(L_t+T_t) \quad (3)$$

$$S_t+p+1 = \gamma(D_t+1/L_t+1) + (1- \gamma)S_t+1 \quad (4)$$

With α = smoothing constant for the level, β = smoothing constant for the tendency and γ = smoothing constant for the seasonal factor.

The ARIMA technique models the regular part and the seasonal part of the time series using the autoregressive component (AR) and moving averages (MA).

3 Analysis of the results

Graph (1) shows the initial descriptive analysis of the time series with a level, a trend, and a certain cyclical seasonality for the three series. This pattern is repeated as shown in figure N°1.

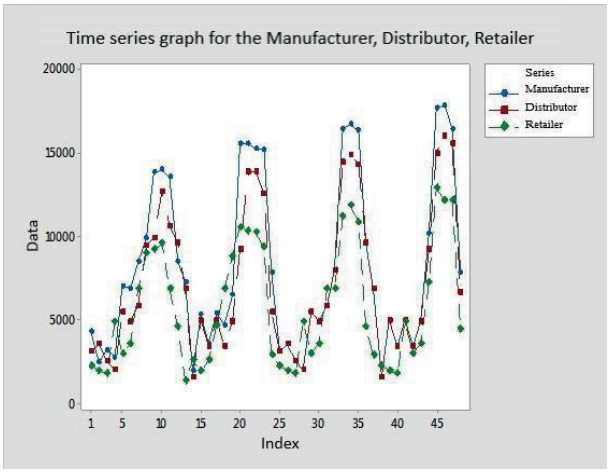

Fig. 1. Time series for the Manufacturer, Distributor, Retailer

For the Holt–Winters method, a smoothing constant was used for the α and β level in the range between (0.1-0.3). The adjustment of the parameters of this model was through simulations; the variation of the parameters had a differential of 0.01 for each iteration. Subsequently, a level of variation of the seasonal factor was determined at a range below 0.21. The best fit was achieved with the values of α = 0.21; β = 0.21, γ = 0.21 for the case of the manufacturer (figure 2).

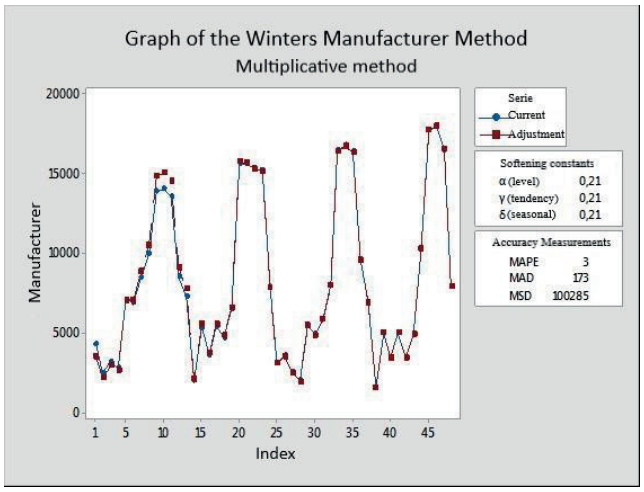

Fig. 2. Manufacturer Forecast

The forecast when using this technique obtained a mean absolute percentage error (MAPE) for the manufacturer, the distributor, and the retailer of 3%, 3%, and 2.7% respectively.

For the ARIMA analysis, the behavior of the time series was identified. The data do not have a normal distribution, as seen in figure Nº3 for the manufacturer's data.

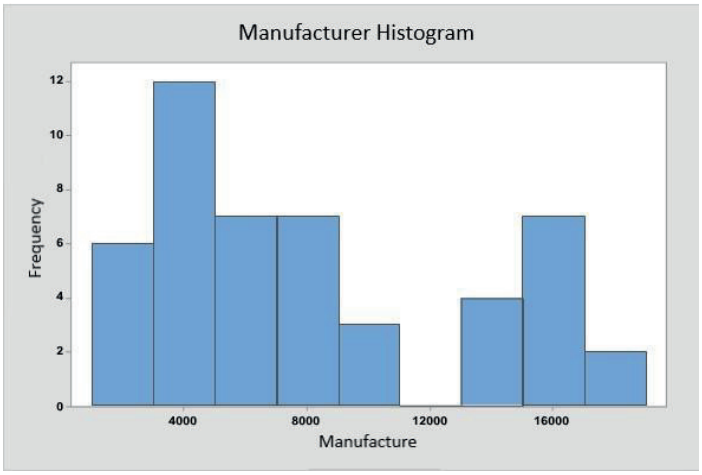

Fig. 3. Manufacturer's Histogram.

A bimodal normal distribution was observed, to carry out the transformation using the Box-Cox method, transforming the data series into a normally distributed model, with $\lambda = 0.5$.

The autocorrelation functions (ACF) and Partial autocorrelation function (PACF), have a mixed model AR and MA structure (Figures 4 and 5).

A bimodal normal distribution is observed, to make the transformation using the Box-Cox method, changing the data series into a normally distributed model, with (lambda) = 0.5.

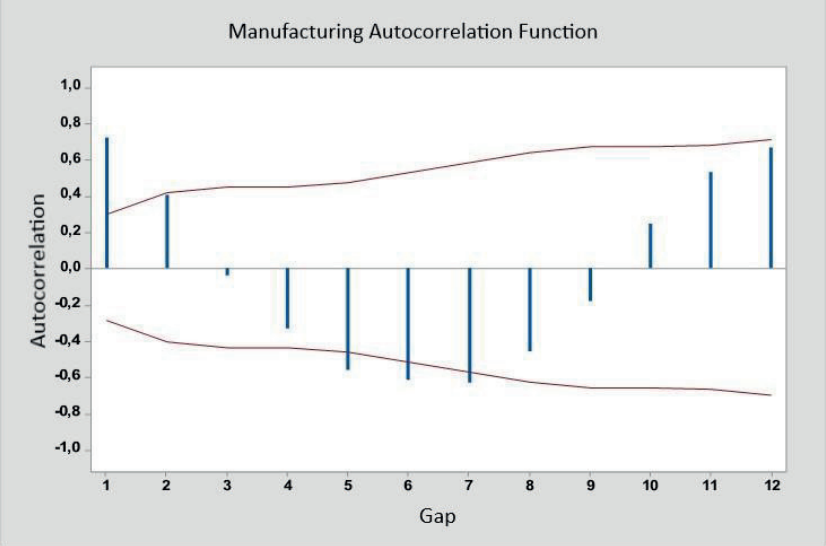

Fig. 4. ACF Producer.

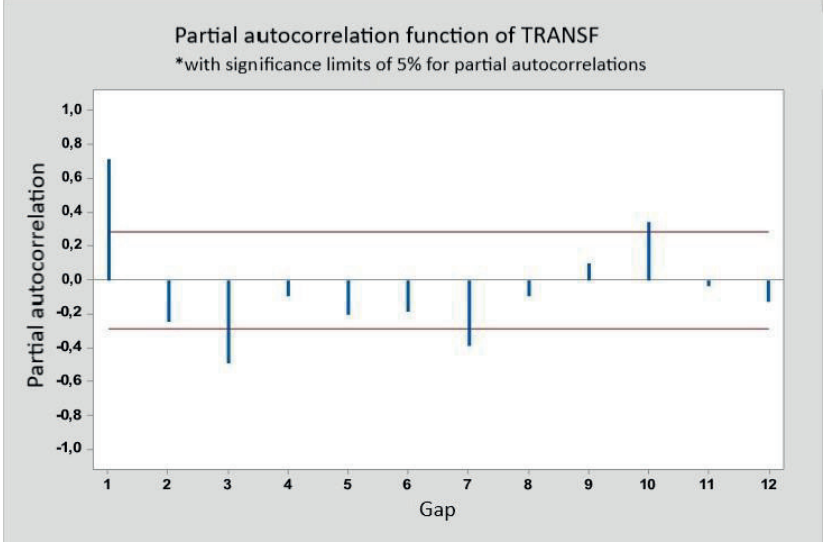

Fig. 5. PACF Producer.

Finally the following models were tested:

- ARIMA (1,0,0) x $(0,1,0)_{12}$
- ARIMA (1,0,1) x $(0,1,0)_{12}$
- ARIMA (1,0,2) x $(0,1,0)_{12}$
- ARIMA (1,0,3) x$(0,1,0)_{12}$
- ARIMA (0,0,3) x $(0,1,0)_{12}$
- ARIMA (1,1,1) x $(1,1,0)_{12}$

All models, except the last one, use the constant. Figure 6 presents the model with the best prognosis.

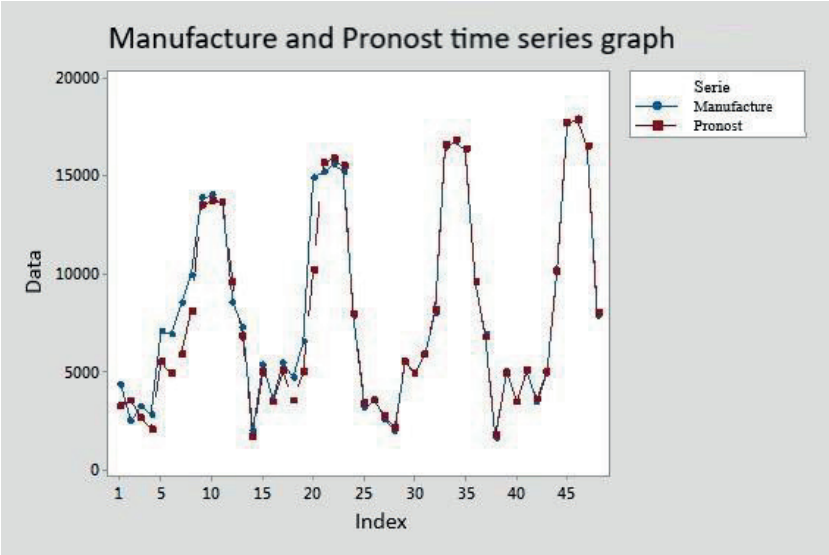

Fig. 6. Manufacturer's forecast using ARIMA model.

For the distributor and distributor series, the transformations were made using the Box-Cox method. However, no correlations were found for the time series using the ARIMA model (table 1). The time series used correspond to the demand for spare parts in the Argentine automotive industry (see annex table 2).

Table 1. The final parameters obtained by the model.

Type	Coefficient	SE Coefficient	Value T	Value P
AR 1	0.385	0.195	2.18	0.056
SAR 12	-0.974	0.102	-9.50	0.000
MA 1	0.942	0.127	.41	0.000

4. Conclusion

This study focused on minimizing the Bullwhip effect by forecasting the demands of the manufacturer, distributor, and retailer based on historical data from the argentine automotive sector. The results obtained were consistent with the theorical literature that refers to the bullwhip effect for the demands at different levels, providing the decision maker with an appropriate methodology for seasonal demands.

Two methods were used, the Holts-Winters method which obtained optimal values for α, β, and γ for the manufacturer, distributor, and retailer. The values for the three stages are $\alpha = \beta = \gamma = 0.21$, with a forecast error of less than 5%.

The ARIMA model for the manufacturer's time series was ARIMA (1,1,1) x $(1,1,0)_{12}$ without a constant end, and was validated with the T contrast test and the p-values. However, ARIMA models could not be found for the other two series after the transformations made with the Box-Cox method.

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Annex

Table 2. N°1 Historical Data of the demand level of a Manufacturer, Distributor, Retailer.

Months	Manufacturer	Distributor	Retailer
1	4320	3125	2254
2	2458	3548	1967
3	3214	2548	1789
4	2771	1987	4887
5	7054	5487	3015
6	6879	4898	3594
7	8461	5874	6874
8	9902	9450	8990
9	13850	9909	9201
10	13975	12694	9586
11	13534	10654	6874
12	8506	9574	4589
13	7251	6874	1345
14	1985	1587	2597
15	5324	4987	1937
16	3587	3456	2597
17	5416	4987	4687
18	4698	3456	6874
19	6487	4897	8794
20	14900	9205	10587
21	15150	13855	10364
22	15550	13871	10234
23	15190	12548	9354
24	7856	5481	2897
25	3125	3125	2254
26	3548	3548	1967
27	2548	2548	1789

28	1987	1987	4887
29	5487	5487	3015
30	4898	4898	3594
31	5874	5874	6874
32	7987	7987	6871
33	16446	14444	11201
34	16694	14897	11856
35	16335	14326	10874
36	9574	9574	4589
37	6874	6874	2897
38	1587	1587	2254
39	4987	4987	1967
40	3456	3456	1789
41	4987	4987	4887
42	3456	3456	3015
43	4897	4897	3594
44	10205	9205	7208
45	17665	14985	12871
46	17865	15995	12201
47	16450	15544	12186
48	7856	6671	4437

Power Scheduling with Interruptions for Residential Demand in Smart Grid

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Abstract. In this paper we deal with a topic of smart grids that considers residential appliance scheduling. As nowadays being interruptible is a quality of many appliances, we analysed the possibility of interrupting the operation of the appliances to represent real-life scenarios in a more faithful way. This could lead to better decisions avoiding the operation of appliances during intervals in which the energy prices were high. We detail the methodology we used and how we generated a diverse instance set with the goal of presenting a realistic analysis. Considering various metrics, we compare the computational results obtained for our model with those belonging to the scenario without interruptions, and explain the positive impact of our incorporation.

Keywords: smart grids, demand response, day-ahead price, residential power scheduling, interruptible appliances, combinatorial optimisation

1 Introduction

In Argentina, as in the rest of the world, energy consumption is constantly rising. This demand is not just boosted by the increase in population but also by the development of new technologies and changes in the ways of living, that become more dependent on electricity.

According to the European Commission (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011SC0463&from=EN), "a Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it — generators, consumers and those that do both — in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety".

Smart grids use new technologies, such as intelligent autonomous controllers, advanced software for optimisation and data management, and bidirectional communications between the electricity companies and the user, with the aim of creating an automatised and distributed energy supply grid [1]. Smart grids allow the adaptation to the changing consumption and generation needs and combine, in a safe way, storage units and renewable energies for distributed generation.

To achieve these goals, the prediction of energy consumption and the determination of energy prices are a key component. The utility companies can have a pricing policy based on the consumption at different times of the day to indirectly control the peak energy demands of the users through a demand response (DR) program. These programs are procedures that can be applied to motivate a change in the energy consumption habits of the users, that respond to incentives such as lower energy prices.

The program implements a pricing policy that *punishes* the energy consumption during peak times, leading the user to reduce the use of appliances in periods of high demand. For this, the user must know this pricing policy beforehand. The implementation of demand response programs has shown to have a significant impact on reducing the costs [2].

Another essential task to achieve the goals of smart grids is scheduling the residential load. To optimise the electricity bill, the user must avoid using appliances in times when the energy is more expensive whenever this is possible or at least operating them at lower powers. To make decisions about residential power scheduling, optimisation algorithms that consider the user's preferences are needed.

Lately there has been plenty of research on optimisation for smart grids. The diverse models proposed, among many differences, have distinct objectives, such as minimisation of the electricity bill, social welfare maximisation, energy consumption minimisation, minimisation of the peak demand, other goals and many combinations.

In [3], distributed generation (DG) and energy storage systems (ESS) are considered and the scheduling model used has as its sole objective the minimisation of the electricity bill. The authors in [4] also consider batteries but focus on a distributed real-time algorithm that allows users to keep to themselves private information regarding their daily schedules. A genetic algorithm is developed in [5] to target energy sharing in a prosumers community.

In [6], the problem of load balancing is tackled by taking into account renewable sources and estimating the energy cost through a combination of real-time pricing (RTP) and incline block rate (IBR), which is a pricing scheme that divides the electricity price into several blocks which are more expensive for higher levels of consumption. RTP and IBR are also used as pricing schemes in [7], where the aim is to schedule household load and integrate renewable energy sources (RESs). An ESS is included and neighbouring consumers can trade surplus generation.

A plug-in hybrid electric vehicle (PHEV) works as an ESS and electricity can be sold to the power grid in [8]. The authors in [9] integrate ESSs and RESs and develop an algorithm which is a combination of a genetic algorithm and a moth-flame optimisation algorithm to minimise the energy cost, the peak-to-average ratio (PAR) and the discomfort, which is a measure of user unpleasantness due to the difference between the desired operation of the appliances and the actual one. In [10], another hybrid algorithm is developed to schedule home appliances but discomfort is not contemplated, the focus is on electricity cost and PAR.

Critical peak pricing (CPP) and RTP are used as pricing schemes. These two pricing tariffs are also used by the authors in [11], where they present a metaheuristic algorithm for controlling the residential loads with the aim of reducing the PAR, the energy consumption and the cost while considering how much time users have to wait for appliances to finish their operation.

In [12], an hour-ahead DR algorithm is proposed. Price forecasting is achieved using artificial neural networks, and decisions for appliance use are based on Reinforcement Learning (RL). RL is combined with Fuzzy Reasoning (FR) by the authors in [13], who develop a home energy management system (HEMS). Their objectives are to avoid energy consumption peaks and to minimise the electricity cost while considering user's preferences.

In this paper we deal with the problem of scheduling residential appliances under a demand response program. We consider a day-ahead pricing scheme and aim to minimise the economic cost of energy and the discomfort felt by users. Appliances are categorised into two groups. Those of the first group are delayable and the discomfort is a consequence of the time the users have to wait for the appliances to end their operation. The others have a flexible power and the discomfort is related to the difference between the actual power of operation and the one it should be. To the best of our knowledge, this paper makes many contributions to the existing literature on residential power scheduling in smart grids. Other papers use other pricing schemes or work with different models regarding possibilities (for example, interrupting appliances or not), formulations (such as using the Taguchi function) or objectives (for example, minimising energy consumption), among other differences.

The remainder of this paper is structured as follows. In Section 2 we present the model considered in [14], modified to have a choosable discretisation for the period of a day and extended to add the possibility to interrupt the operation of some appliances. The solution methodology we used is explained in Section 3, in which we design two polynomial-time algorithms and present their foundations. In Section 4 we describe the set of instances we designed to represent real-life scenarios in a more faithful way, taking into account different needs and priorities regarding the use of electric appliances. Computational results for those instances are presented in Section 5 with an analysis that considers various metrics and compares both algorithms. We finalise this paper with conclusions and ideas to continue our work, explained in Section 6.

2 Two Types Appliance Scheduling for Economic and Disconfort Minimisation With Interruptions (2TASEDMWI)

In [14], the authors present a problem that we shall call Two Types Appliance Scheduling for Economic and Disconfort Minimisation (2TASEDM). They consider an intelligent system for the purpose of assisting a user in a decision-making process regarding their use of different electric appliances. The goal is to min-

imise the discomfort felt by the user and also their electricity bill by considering certain priorities according to a desired-tradeoff.

The system knows the electricity prices p^t of consuming one kW during each interval t between two consecutive instants t and $t+1$ of a certain time window $\mathcal{T} = \{0, ..., T\}$, fixing $T = 23$ to represent each hour of a day, horizon in which the user will schedule their appliances.

In [14], the user has two types of electric appliances. Those of the first type, grouped in set $\mathcal{A}_1$, have a flexible operation time and work continuously with a fixed power. Appliances of the second type, clustered in $\mathcal{A}_2$, have a predefined working time with flexible power which may be different for each interval.

Each appliance a can operate within a certain interval $[\alpha_a,\ \beta_a)$ included in the time window $[0,\ T+1)$. An appliance $a \in \mathcal{A}_1$ must operate T_a consecutive intervals with a fixed power r_a and α_a represents the desired starting time. In contrast, as is mentioned in [14] by the authors, those with flexible power must operate during the whole interval $[\alpha_a,\ \beta_a)$ with powers between r_a^{min} and r_a^{max}.

The model proposed in [14] does not consider interrupting the operation of appliances, even when being interruptible is a quality of many appliances. This could lead to better decisions avoiding the operation of appliances during intervals in which the energy prices were high. For these reasons, we proposed a new model adding the possibility of interrupting the operation of the appliances of $\mathcal{A}_1$. We shall call this new problem 2TASEDMWI (Two Types Appliance Scheduling for Economic and Disconfort Minimisation With Interruptions).

We also think that hourly discretisation as proposed in [14] is not the most suitable one when dealing with electric appliances, given that some, such as electric ovens, have shorter operation times. Instead, we propose using a discretisation that provides greater granularity to represent real-life scenarios in a more faithful way. Such granularity will be a parameter of our algorithms and, according to the scenario to be modeled, the appropriate value will be set.

To precisely formulate the objective function, first we define some variables. For each appliance a and each interval $t \in \mathcal{T}$, we define $x_a^t \in \mathbb{R}_{\geq 0}$, the power of operation. In addition, for each appliance $a \in \mathcal{A}_1$ we shall define the variable $t_a \in \mathbb{Z}_{\geq 0}$, the ending time of operation.

As we mentioned earlier, there are two goals: the reduction of the electricity bill and the decrease in the discomfort.

The electricity bill results from the energy consumption levels and the electricity prices in each interval. It is calculated as the sum over all intervals of the product of the price and the energy used:

$$V_p = \sum_{t \in \mathcal{T}} \left(p^t \sum_{a \in \mathcal{A}_1 \cup \mathcal{A}_2} x_a^t \right) \tag{1}$$

The discomfort is different for the two types of appliances: for the first type it arises from the delay in the operation ending time with respect to the user's wish and for the second type it is related to the difference between the power used and the normal power consumption in each interval.

In the mentioned paper, the authors present an hourly discretisation and propose the following formula to model the discomfort for a certain appliance

$a \in \mathcal{A}_1$

$$V_a = \rho_a \ \big(t_a - (\alpha_a + T_a)\big)^{k_a} \tag{2}$$

where $0 < \rho_a < 1$ and $k_a \geq 1$ are real numbers related to the operational characteristics of a.

To achieve a metric that is independent of the discretisation, we incorporate a constant *iph* that represents the number of intervals included in one hour according to the chosen discretisation, so that the number of hours of delay is expressed instead of the number of intervals. We also want a greater discomfort for a bigger value of k_a, and no discomfort in the case of having no delay, so we propose the following formula:

$$V_a = \rho_a \ \Big[\ \Big(1 + \frac{t_a - (\alpha_a + T_a)}{iph}\Big)^{k_a} - 1\Big] \tag{3}$$

For appliances in $\mathcal{A}_2$, the discomfort related to their powers of operation is expressed through the Taguchi loss function [15].

In each interval t, if $\widehat{x}_a^t$ stands for the normal power consumption of a certain appliance a, $\widehat{x}_a^t \pm \Delta_a^t$ designates the extremes at which the appliance will suffer functional failure. Then, the user must take some countermeasure if the power of an appliance is $\widehat{x}_a^t + \Delta_a^t$ or $\widehat{x}_a^t - \Delta_a^t$, and its cost is denoted A_a^t.

If the parameter ω_a^t is defined as

$$\omega_a^t = \frac{A_a^t}{{\Delta_a^t}^2} \tag{4}$$

then the discomfort caused by the operation of the appliance a in the interval $t \in \{\alpha_a, ..., \beta_a - 1\}$ is formulated as

$$V_a^t = \omega_a^t \ (x_a^t - \widehat{x}_a^t)^2 \tag{5}$$

The total discomfort for an appliance $a \in \mathcal{A}_2$ is the sum of the discomfort over the operation intervals:

$$V_a = \sum_{t=\alpha_a}^{\beta_a - 1} \omega_a^t \ (x_a^t - \widehat{x}_a^t)^2 \tag{6}$$

The authors in [14] also mention that the restrictions on the powers of the appliances of $\mathcal{A}_2$ are only valid if $2 \ (\widehat{x}_a^t - r_a^{min}) \ \omega_a^t < p^t$.

The objective is to determine the values of the variables x_a^t and t_a that minimise a convex combination of the electricity bill and the discomfort. In other words, the goals have weights $\alpha_1, \ \alpha_2 \in \mathbb{R}_{\geq 0}$, $\alpha_1 + \alpha_2 = 1$, and the objective is to minimise the weighted sum.

3 Methodology for 2TASEDMWI

In the following we detail the methodology we used and provide the time complexity as well as the auxiliary space for each algorithm.

In the optimisation problem presented, each appliance can be optimised independently of the others. Also, for an appliance $a \in \mathcal{A}_2$, the optimal powers can be found independently for the different operation intervals.

We developed two algorithms for the appliances of $\mathcal{A}_1$ using dynamic programming: one prioritises the execution time at the expense of greater memory usage, while the other one restricts the memory utilised. Both make use of the fact that given the economically optimal solution for a certain possible ending time t, s_t, the one for the time $t+1$ is obtained removing the most expensive interval used in s_t and adding the interval t.

For both algorithms we consider that a solution for an appliance a is a dictionary of key-value pairs in which the keys are energy prices. For each key p, the value is a set of intervals, each with price p, in which a is active. Moreover, the solution has an economic cost which is the sum of the energy prices of the intervals in which the appliance was used.

If the implementation is done with appropriate data structures like ordered associative containers and binary search trees, efficient algorithms are obtained.

We first present the algorithm that uses less memory. Algorithm 1 assumes, without loss of generality, that $\alpha_a + T_a \leq \beta_a$ for all appliances a of the first type included in the instance being solved. If this were not the case, the instance would be infeasible.

Algorithm 1

create 2 empty solutions s and $sOpt$
totalCost $\leftarrow 0$
optimalCost $\leftarrow 0$
for $t \leftarrow \alpha_{a1} \dots \alpha_{a1} + T_{a1} - 1$ **do**
    add t to s
end for
totalCost $\leftarrow \alpha_1 * s$.economicCost $* r_{a1}$
$sOpt \leftarrow s$
optimalCost $\leftarrow$ totalCost
optimalEndingTime $\leftarrow \alpha_{a1} + T_{a1}$
for $t \leftarrow \alpha_{a1} + T_{a1} \dots \beta_{a1} - 1$ **do**
    remove from s an interval that is the most expensive among those of s
    add t to s
    totalCost $\leftarrow \alpha_1 * s$.economicCost $* r_{a1}$ + discomfort for $a1$ for finishing at $(t+1)$
    if totalCost $<$ optimalCost **then**
        optimalEndingTime $\leftarrow t + 1$
        optimalCost $\leftarrow$ totalCost
    end if
end for
for $t \leftarrow \alpha_{a1} + T_{a1} \dots optimalEndingTime - 1$ **do**
    remove from $sOpt$ an interval that is the most expensive among those of $sOpt$
    add t to $sOpt$
end for
return optimalCost and intervals of activity of $sOpt$

This algorithm can be implemented with a time complexity of

$$\mathcal{O}\Big[\Big(\sum_{i=1}^{T_a} log(i)\Big) + T_a + (\beta_a - 1 - (\alpha_a + T_a)) * (1 + log(T_a))\Big] \tag{7}$$

Considering that $T_a \leq \beta_a - \alpha_a$, a weaker bound for the time complexity is

$$\mathcal{O}\big((\beta_a - \alpha_a) * log(T_a)\big) \tag{8}$$

Regarding memory, the auxiliary space complexity is $\mathcal{O}(T_a)$.

Next we detail other algorithm, which uses more auxiliary space. It can result in lower execution times for instances where there are many appliances which share the time windows of possible operation, given that it makes use of information independent of the parameters relative to the discomfort of each appliance.

Given α_a, β_a and T_a, finding the activity intervals of optimal functioning makes it easier to find those for appliances with the same parameters of start and duration but earlier ending. This is due to the fact that during the process of solving the problem for the combination (α_a, β_a, T_a) it is possible to calculate, for each possible instant of finalisation t, the minimum economic cost and the associated activity intervals, as seen in the previous algorithm.

Therefore, given an appliance a' with parameters $\alpha_{a'} = \alpha_a$, $T_{a'} = T_a$ and $\beta_{a'} \leq \beta_a$, the possible instants of operation finalisation $t_{a'}$ between $\alpha_a + T_a$ and $\beta_{a'}$ should be examined. For each of these, the global cost would be calculated from the economic cost associated with the duration T_a and from the discomfort resulting from finishing the operation in t_a.

For this algorithm we have two dictionaries. One contains the economically optimal solution for each combination (α, t, T) of possible start of operation (α), instant of possible end of operation (t) and duration (T). The other contains the maximum t for each α and T, since from this solution we will remove and add intervals to obtain the solutions with posterior ending times.

As before, as $T_a \leq \beta_a - \alpha_a$, with an efficient implementation of this algorithm we can obtain an upper bound on the temporal complexity of

$$\mathcal{O}\big((\beta_a - \alpha_a) * T_a\big) \tag{9}$$

Even when the complexity for a single appliance is worse than the one we have for the other algorithm, the motivation for this algorithm lies in the use for scenarios with many appliances. Moreover, when the data structures already have the information stored, the complexity will be that of evaluating the costs for the $\beta_a - (\alpha_a + T_a)$ possible ending times added to that of copying the optimal solution:

$$\mathcal{O}\big((\beta_a - (\alpha_a + T_a)) + T_a\big) \tag{10}$$

For each appliance of the second type and each of its operation intervals, the total cost is a quadratic function on variable x_a^t:

$$c(x_a^t) = \alpha_1 \; p^t \; x_a^t + \alpha_2 \; \omega_a^t \; (x_a^t - \widehat{x}_a^t)^2 \tag{11}$$

where its domain is $[r_a^{min},\ r_a^{max}]$ if the restrictions for the power are active, otherwise it is $[0, +\infty)$.

We can obtain the analytical solution for the minimisation of the total cost function with constant time complexity and auxiliary space.

4 Instance set

With the goal of having bigger and more realistic instances than those presented in [14], in this paper we set $T = 143$, being able to distinguish each 10-minute interval, and we consider instances of different sizes.

First we design 3 types of houses: the house of a person that goes to work during the day, called *diurnal house*; the house of a person that goes to work during the night, named *nocturnal house*; and the house of a person that doesn't work outside the house, to which we refer to as *full day house*.

The houses have 13 schedulable appliances. The appliances of the first type are a robot vacuum (RV), a robotic pool cleaner (RP), a computer (C), a television (TV), a washing machine (WM), an iron (I), an electric stove (ES) and a water heater (WH). The appliances with a flexible power are lights (L), an air conditioner (AC), a dishwasher (DW), a treadmill (T) and an hydromassage table (HT).

The parameters of the appliances for the diurnal house, detailed in Tables 1 and 2, arise from considering that it belongs to someone who sleeps from 12 a.m. until 8 a.m. and works from 9 a.m. until 5 p.m., arriving home at 5:30 p.m. The robots are charged, preferably while the owner has breakfast just in case there are any problems, and are fully charged when the user arrives home. Then the treadmill is used from 6:30 p.m. to 6:50 p.m. After that, the clothes are washed and it is time for a massage. Between 6:30 p.m. and 9:30 p.m. dinner is cooked, and at 9 p.m. the dishwasher starts functioning. Also, from 8 p.m. until going to sleep, the user wants to use the computer and the television, iron clothes and take a shower.

For clarity purposes we choose to show the times represented by α and β instead of their respective numbers of intervals. In other words, with the selected discretisation which considers an instant every 10 minutes, for $\alpha = 48$ we show 8 a.m. We also changed the representation for the parameter T opting for the hours and minutes format.

Likewise, even though there could be different values for the parameters $\widehat{x}^t$ and ω^t throughout the day, we only show one for each parameter as it was the same during the whole operation time.

In the same way, in Tables 3, 4, 5 and 6 we present the parameters of the appliances of the nocturnal house and the full day house. For the full day house, it is reasonable to think that the operation time windows would be wider and the operation times would be greater, given that the owners spend more time in their homes than the people that leave for work. Another consequence is that their concern about the time at which they do certain activities is less than that of the people that leave for work.

Table 1. Parameters of the appliances of $\mathcal{A}_1$ considered for the diurnal house

	RV	RP	C	TV	WM	I	ES	WH
α	8 a.m.	8 a.m.	8 p.m.	8 p.m.	7 p.m.	7 p.m.	6:30 p.m.	10 p.m.
β	5 p.m.	5 p.m.	12 a.m.	12 a.m.	11:30 p.m.	9 p.m.	9:30 p.m.	11:30 p.m.
T	1:40	1:40	1:00	1:40	1:20	1:00	00:30	00:30
r (kW)	1.4	0.4	0.38	0.16	0.7	1	1.2	1
ρ	0.001	0.001	0.8	0.75	0.1	0.7	0.4	0.2
k	1.3	1.3	3	2.8	1.9	3.6	2.1	1.8

Table 2. Parameters of the appliances of $\mathcal{A}_2$ considered for the diurnal house

	L	AC	DW	T	HT
α	7:00 p.m.	6:20 p.m.	9 p.m.	6:30 p.m.	7:20 p.m.
β	12 a.m.	8:50 p.m.	10:20 p.m.	6:50 p.m.	7:50 p.m.
r^{min} (kW)	0.3	0.3	0.3	0.3	0.3
r^{max} (kW)	0.9	1.1	0.9	0.9	0.9
$\widehat{x}^t$ (kW)	0.5	0.7	0.8	0.8	0.5
ω^t (\$/kW^2)	1.6	2	0.8	1.9	1.1

We also design neighbourhoods replicating the 3 original houses and changing the parameters of their appliances. To achieve a better model of reality, 70% of the houses of the neighbourhoods are diurnal houses, 10% are nocturnal houses and 20% are full day houses.

For the diurnal and nocturnal houses, the parameters α and β can be changed at random any number of intervals up to one hour or not be changed at all, all the options are equiprobable. If α results less than 0 or greater than $|\mathcal{T}|$, it is assigned that value. The same happens for β if it is less than 1 or greater than $|\mathcal{T}| + 1$. The duration for the appliances of $\mathcal{A}_1$ may remain unchanged or be modified a certain number of intervals up to 10 minutes for every whole hour of operation of the original appliance and all the options are equiprobable. The minimum possible duration is an interval and the greatest is $|\mathcal{T}|$. In the case that after the modifications for some appliance a, the inequality $\alpha_a + T_a \leq \beta_a$ is not satisfied if $a \in \mathcal{A}_1$ or $\alpha_a \leq \beta_a$ if $a \in \mathcal{A}_2$, the parameters of the original appliance are copied to the new one.

Table 3. Parameters of the appliances of $\mathcal{A}_1$ considered for the nocturnal house

	RV	RP	C	TV	WM	I	ES	WH
α	12 a.m.	12 a.m.	1 p.m.	1 p.m.	10:30 a.m.	2:30 p.m.	1 p.m.	10:40 a.m.
β	9 a.m.	9 a.m.	4:30 p.m.	4:30 p.m.	2:30 p.m.	4 p.m.	2 p.m.	12:40 p.m.
T	1:40	1:40	1:00	1:40	1:20	1:00	00:30	00:30
r (kW)	1.4	0.4	0.38	0.16	0.7	1	1.2	1
ρ	0.001	0.001	0.8	0.75	0.1	0.7	0.4	0.2
k	1.3	1.3	3	2.8	1.9	3.6	2.1	1.8

Table 4. Parameters of the appliances of $\mathcal{A}_2$ considered for the nocturnal house

	L	AC	DW	T	HT
α	9 a.m.	12 p.m.	2:20 p.m.	10 a.m.	10:30 a.m.
β	11 a.m.	2:30 p.m.	3:40 p.m.	10:20 a.m.	11 a.m.
r^{min} (kW)	0.3	0.3	0.3	0.3	0.3
r^{max} (kW)	0.9	1.1	0.9	0.9	0.9
$\widehat{x}^t$ (kW)	0.4	0.7	0.8	0.8	0.5
ω^t (\$/kW^2)	1	2	0.8	1.9	1.1

Table 5. Parameters of the appliances of $\mathcal{A}_1$ considered for the full day house

	RV	RP	C	TV	WM	I	ES	WH
α	7 a.m.	7 a.m.	4 p.m.	4 p.m.	5 p.m.	4 p.m.	6:30 p.m.	10 a.m.
β	6 p.m.	6 p.m.	12 a.m.	12 a.m.	10:30 p.m.	9 p.m.	9:30 p.m.	10:30 p.m.
T	1:40	1:40	1:30	2:10	1:20	1:20	00:50	00:40
r (kW)	1.4	0.4	0.38	0.16	0.7	1	1.20	1
ρ	0.001	0.001	0.7	0.65	0.1	0.6	0.5	0.2
k	1.15	1.15	2.7	2.4	1.75	3.3	1.9	1.6

The rest of the parameters are obtained uniformly at random as a value between 93% and 107% of the original value, with possible posterior changes to guarantee their validity. For ρ, the maximum value between the result and 0.0001 is taken, and then the minimum between that result and 0.9999. For k, it is the maximum between the result obtained and 1. For r_{min} and r_{max}, if $r_{min} > r_{max}$ then the original values are restored. Likewise, if $\widehat{x}^t < r_{min}$, r_{min} is assigned to $\widehat{x}^t$, and if $r_{max} < \widehat{x}^t$, r_{max} is assigned to $\widehat{x}^t$. Finally, for ω^t the maximum is taken between the value obtained and 0.001.

For the full day houses, the appliances are changed similarly.

For those of $\mathcal{A}_1$, α is advanced in time a certain number of intervals uniformly at random up to 2 hours (possibly 0), and analogously β is delayed. For the appliances of $\mathcal{A}_2$ the changes were up to one hour. As before, α is not less than 0 and β is not greater than $|\mathcal{T}|+1$. The activity duration of the appliances of the first type was extended some number of intervals (possibly 0) equiprobably up to 30 minutes for every whole hour of operation. If the duration of the original appliance was less than an hour, it was extended an interval for the new

Table 6. Parameters of the appliances of $\mathcal{A}_2$ considered for the full day house

	L	AC	DW	T	HT
α	6 p.m.	5:50 p.m.	8 p.m.	6 p.m.	6:40 p.m.
β	11:30 p.m.	9:20 p.m.	9:20 p.m.	6:30 p.m.	7:30 p.m.
r^{min} (kW)	0.3	0.3	0.3	0.3	0.3
r^{max} (kW)	0.9	1.1	0.9	0.9	0.9
$\widehat{x}^t$ (kW)	0.6	0.8	0.8	0.5	0.35
ω^t (\$/kW^2)	1.7	2	0.8	1.4	0.9

appliance. The final duration was the minimum between the new duration and the size of the time window of possible operation $\beta - \alpha$.

The parameter r is obtained randomly as some value between 90% and 104% of the original value. For each of the remaining parameters ρ and k, a uniform random value between 86% and 100% of the original is obtained and then we proceed as explained before to guarantee their validity.

Finally, r_{min} and r_{max} are changed as for the other types of houses. The normal power consumption $\widehat{x}^t$ is obtained as a value between 85% and 99% of the original value and we ensure it will be in the range $[r_{min},\ r_{max}]$ as we explained before. On the other hand, ω^t is fixed as the maximum between 0.001 and a value between the original ω^t and 114% of it.

We randomly generated 5 instances for each neighbourhood size, starting with 10 houses and increasing by 10 up to 500, then adding $5,000$ houses starting at $5,000$ until $50,000$ and finally augmenting from $100,000$ up to $1,000,000$ with steps of $50,000$.

Finally, we considered electricy prices characteristic of the society of Buenos Aires, Argentina. These are shown in Figure 1 and correspond to a demand-response program.

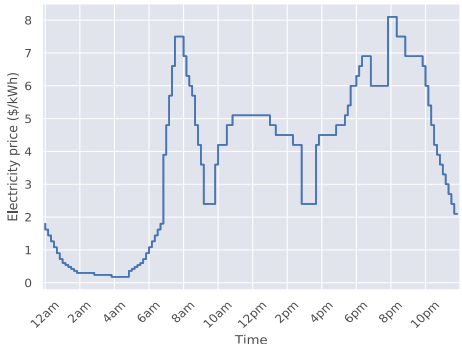

Fig. 1. Electricity prices in the different subintervals of the time window

5 Computational Results for 2TASEDMWI

In this section we compare the results obtained for the scenario with interruptions with those for the scenario without interruptions, and also for the algorithms designed.

For all the experiments presented in this paper we used a computer with *Intel Core i*7 7700, 3.60GHz and 16 GB RAM. The metrics studied were the value of the objective function, the electricity bill, the total discomfort, the peak energy demand in one interval, the peak-to-average ratio, the execution time and the memory used. For each metric we took the average of the values for the executions for the different instances with a common size.

As in [14], we consider three operation modes according to different priorities. In the first one, called "Economic" (E), the consumer only cares about the electricity bill and so we set $\alpha_1 = 1$, $\alpha_2 = 0$. In the second operation mode, the user is only concerned about discomfort and we set $\alpha_1 = 0$, $\alpha_2 = 1$, so this mode is called "Comfort" (C). In the third one, "Balance" mode (B), the user is equally worried about the electricity bill and the discomfort, resulting $\alpha_1 = \alpha_2 = \frac{1}{2}$.

In the figures shown, the continuous lines (NI) belong to the scenario with non interruptible appliances and the other lines (I) belong to the scenario with interruptible appliances. Also, because the two algorithms designed for the scenario with interruptible appliances always find the same optimal solution, all the metrics dependent on the composition of the solutions (for example, the electricity bill) and not relative to obtaining the solutions (such as the execution time) resulted equal. Moreover, the results for those metrics for the comfort mode were the same for both scenarios, something that can be verified in the plots, in which the continuous line labeled "NI - C" overlaps with the intermittent line labeled "I - C". This can be explained taking into account that in that operation mode, appliances end their operation time as soon as possible, and this is achieved starting as soon as possible and not interrupting the operation. Because of this, the analysis for these metrics when comparing both scenarios is only made for the other operation modes.

Figure 2 shows a reduction in the value of the objective function that is due almost entirely to a decrease in the electricity bill, as it can be seen in Figures 3 and 4.

Figure 5 shows that the peak energy demand increased for the balance mode for the scenario with interruptible appliances but decreased for the economic mode. This could be due to the fact that the balance mode distributed the activity between less cheaper intervals because after a certain moment, discomfort became very high.

Given that for a certain operation mode the total energy consumption is the same with and without interruptions, the differences in the peak energy demand led to differences in the PAR, as it can be observed in Figure 6. Contrary to what happens in the scenario without interruptions, in the scenario with interruptions the economic mode presents a lower peak demand that the balance mode. Even so, as it happens in the scenario without interruptions, it results in a greater PAR. Again, this can be explained by the difference in the total energy consumption for both operation modes. It should be mentioned that the increase of the PAR for the balance mode when interruptions are allowed is less than the decrease of the PAR for the economic mode.

Overall, the incorporations of interruptions is undeniably beneficial. Users, specially those with hard economic situations, would be particularly relieved by a decrease in their electricity bills.

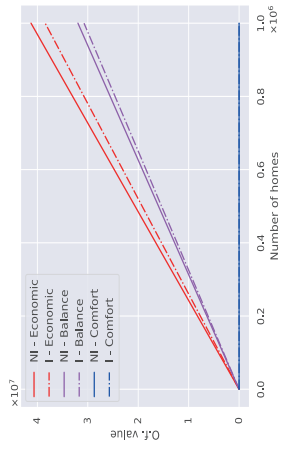

Fig. 2. Value of the objective function for each scenario

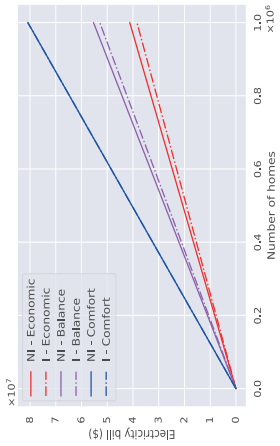

Fig. 3. Electricity bill for each scenario

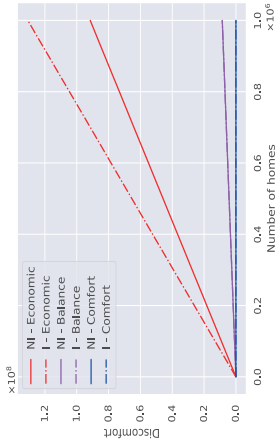

Fig. 4. Discomfort for each scenario

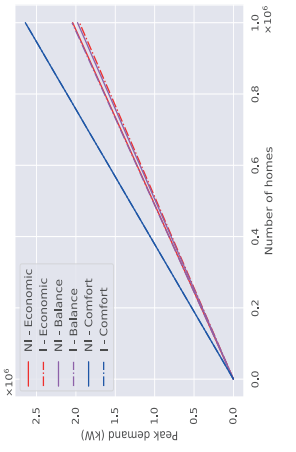

Fig. 5. Peak energy demand for each scenario

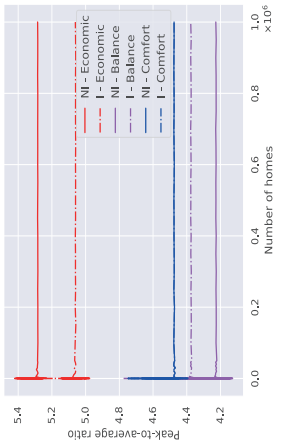

Fig. 6. PAR for each scenario

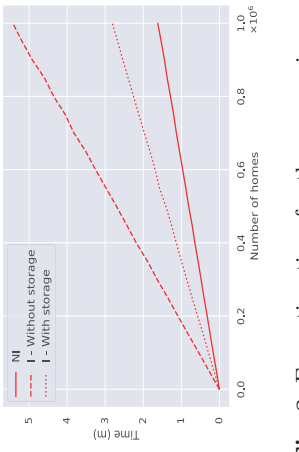

Fig. 8. Execution time for the economic mode

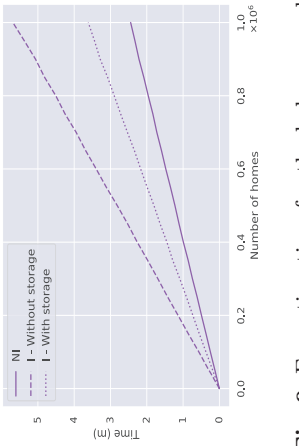

Fig. 9. Execution time for the balance mode

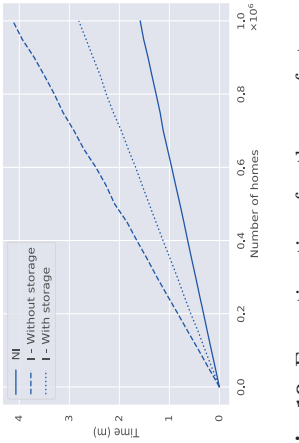

Fig. 10. Execution time for the comfort mode

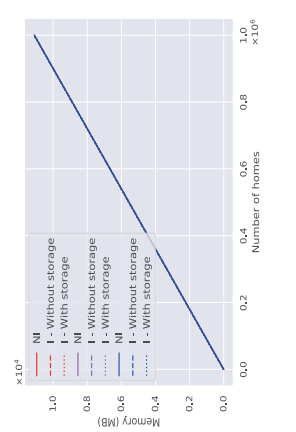

Fig. 7. Memory used for all algorithms

Regarding the algorithms, the execution times for the algorithms for the scenario with interruptions were in fact greater than those of the algorithm for the scenario without interruptions, as shown in Figures 8, 10 and 9. Even though there was a significant difference between the execution times of the algorithm for non-interruptible appliances and those of the one for interruptible appliances with less information storage, the difference was less that half when comparing the former with the algorithm for interruptible appliances with more information storage. Moreover, Figure 7 shows that the memory used was almost the same considering the sizes of the instances and the resources of most computers nowadays. It is also worth mentioning that for these computational resources the dependence with the number of homes appears to be linear.

Even though the execution times were different for the algorithm without interruptions and the algorithm with interruptions and additional data structures, this is due to two factors. One is related to the information storage on the additional data structures. Given that once completed, their sizes do not depend on the number of appliances, the contribution to the execution time would eventually be negligible when considering more homes. This is consistent with the fact that the complexity calculated for the algorithm when the information is already stored is almost the same as that for the algorithm for non-interruptible appliances. The other factor is related to the fact that storing the information to report the solution in the scenario without interruptions only consists in storing, for example, the instant of finalisation of activity of each appliance, since the operation intervals can be obtained from that. This is not true for the scenario with interruptions, which requires storing all activity intervals of each appliance.

6 Conclusions

In this paper, we decided to allow interruptions in the operation of delayable appliances because this models real-life scenarios in a more faithful way. Despite the fact that allowing interruptions proved to be advantageous regarding many metrics, the peak energy demand and the PAR worsened for the balance mode. Furthermore, the economic mode could create high peaks of energy demand as a result of choosing the cheapest intervals as operation intervals for many appliances. Even without interruptions, the confort mode could also generate energy demand peaks as a result of using excessive energy during some intervals. It would be reasonable if the electricity provider established a bound on the energy consumption for each interval to avoid oversizing the power grid, as that would not be exploited during most of the day. It becomes interesting to consider these energy consumption bounds, which are the center of our future research.

Acknowledgments

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Residents' perception from a Brazilian municipality about the COVID-19 social distancing period

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Abstract. The municipal government of Caruaru (PE), Brazil, has made several efforts to control the spread of the new coronavirus (COVID-19) in the municipality. The first action was the creation of a crisis management committee. Since then, Caruaru adopted some preventive actions, such as: suspension of classes in public and private schools and universities; prohibition of local commerce activities and non-essential services; creation of digital platforms to enable the commercialization of goods and services; cleaning and disinfection of public areas; investigation of people crowding; proposition of awareness campaigns and assistance to the vulnerable population. Despite all these preventive actions and the numerous awareness campaigns, there are a large number of reports of disrespect for the actions imposed. Does the population understand the need for social distancing? Do they understand the risk of the disease? Several strategies can guide individual actions and they have a direct and real reflection on the social distancing. Therefore, this study aimed to understand the residents' perceptions of social distancing and, consequently, the resumption of economic activities in the municipality. The results show that the population understands contagion risk from COVID-19, understands the need for social distancing, and prophylactic measures to reopen the commercial activities and recognize myths of the disease. However, there is a failure to comply with the actions imposed by the municipality.

Keywords: COVID-19, Public management, Social distancing, Public health.

1 Introduction

The spread of the new coronavirus (COVID-19) forced governments to develop public policies to slow down the disease transmission and reduce overcrowding in health systems. One of the recommended strategies for all countries, regions, cities, and communities is to reduce social contacts, that is, to perform a social distancing [1].

The first suspected and confirmed case of COVID-19 in Latin America was in Brazil [2]. The COVID-19 is spreading very fast in Brazil [3], and the country is in a

crucial moment to minimize the impact of the illness on society by reducing the number of cases and, thus, preventing deaths [4].

In the state of Pernambuco (PE), Brazil, it was no different. The first COVID-19 cases registered in the state date from March 12, 2020. As a result, a series of preventives actions were adopted by both the state and municipal governments.

Caruaru is a Brazilian municipality, located in the state of Pernambuco, with an estimated population in 2019 of 361,118 people [5]. The Municipality of Caruaru published a decree nº024 on March 15 with the first actions to combat COVID-19 (Caruaru had no COVID-19 cases at this moment). Several additional decrees were proposed to limit people's circulation and crowding. On March 23, the city registered its first confirmed case of COVID-19. The municipality started to publish daily bulletins of the situation of COVID-19 in the city in April 12[6]. Fig. 1 shows the evolution of COVID-19 cases in Caruaru, where on August 09 where 5,231 cases and 256 deaths were recorded.

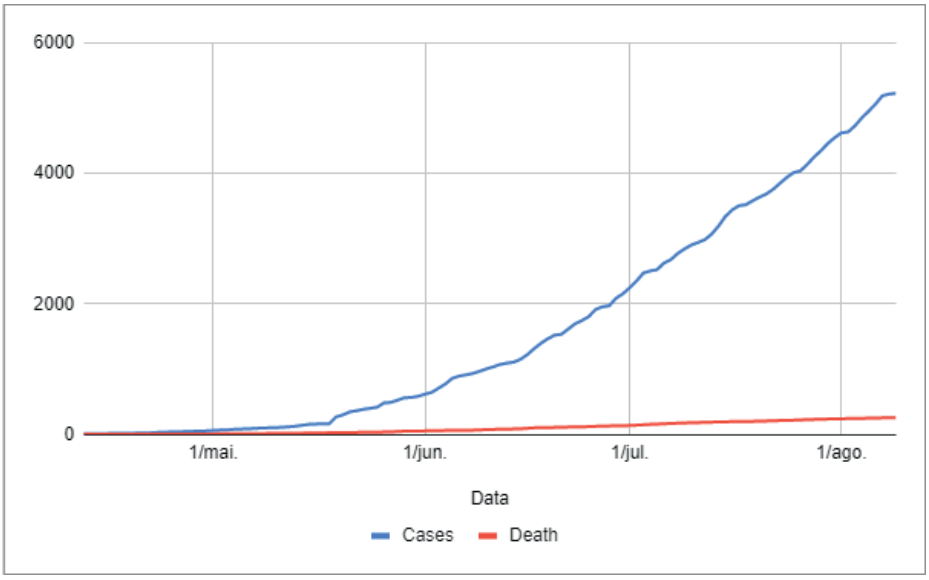

Fig. 1. Evolution of COVID-19 cases in Caruaru (PE).
Fonte: Adapted from [6].

Despite all the efforts of the municipality's management to make social distancing effective, the number of COVID-19 cases increased exponentially (see Fig.1) and several complaints of people crowding were reported in this period. Although the main objective is to save lives, the biggest conflict is about the social distancing impacts the local economy. As a result, there are countless debates about the severity of the actions adopted and what would be the right time to "loosen them up", i.e., when to a resumption of economic activities, mainly trade, since there are still no proven effective drugs or vaccine [7].

Maloney and Taskin [8] related that fear or social responsibility are the main responsible for effective voluntary individual actions of social distancing. Also, they

showed that public campaigns on protective actions (e.g. face masks), can make people feel more confident, increasing social mobility. "Therefore, it becomes crucial to understand people's worries about the pandemic and their perceptions of the effects of containment policies, so that the design of further policies and contingency actions well-informed, and a high level of compliance can be expected from the population" [7].

Therefore, this paper developed a questionnaire that was applied to residents of Caruaru (PE), in June 2020, intending to understand the public sentiment toward the actions used by policymakers for COVID-19 containment, and how they assess the risk of resumption economic activities in the municipality.

The results can help to guide the actions of the local public management, carrying out specific awareness campaigns, as well as directing actions regarding the rules for the resumption of economic activities in the municipality.

The paper was divided into four sections, the first being this introduction. Section 2 reports on materials and methods. Section 3 presents the results of the research. Finally, the discussions and conclusions are made in section 4.

2 Material and Methods

This research is characterized by survey research through a structured questionnaire. In this paper, a descriptive approach to results was used.

Also, it was assessed whether there is a correlation between the respondents' age and the observed variables. For the correlation analysis, the Kruskal-Wallis non-parametric test and Spearman's correlation were used. A significance level of 5% probability for rejection of the null hypothesis was adopted as a reference.

2.1 Research questionnaire

Questionnaires are one of the most used means of collecting data. They can contact and collect responses from a relatively large number of people in dispersed and possibly remote locations [9].

To build the questionnaire for this study, the steps recommended by [10] were followed. The questionnaire was assigned the self-administration method, i.e., the data collection instrument was conducted by the respondents themselves.

The questionnaire consists of 34 items, 06 of which are sociodemographic and 28 of specific knowledge, divided into the following categories: (1) cases of the disease and fear of contracting the COVID-19; (2) assessment of social distancing in the municipality; (3) evaluation of trade reopening actions; (4) Contagion risk assessment; (5) assessment of knowledge about COVID-19.

The final version of the questionnaire was applied in the city of Caruaru, in the state of Pernambuco, Brazil, in June 2020. Through random sampling, the questionnaire was answered by 268 residents. Considering the current population of Caruaru of 361,118 inhabitants and a confidence interval of 95%, the sampling error is 6%, our sample is close to the real representation of the population, but it is not enough for full population extrapolation.

2.2 Questionnaire analysis

The internal consistency of the questionnaire was estimated using Cronbach's alpha [11]. A value of $\alpha > 0.70$ is generally considered acceptable [12]. To calculate the Cronbach's alpha, the Statistical Package for the Social Sciences (SPSS) software version 16.0, 2007 was used.

The questionnaire had $\alpha = 0.728$, showing an acceptable internal consistency.

3 Results

3.1 Sociodemographic analysis

The demographic data of the respondents are shown in Table 1.

Table 1. Sample demographics

Variables	Percentage	Variables	Percentage
Genre		Education degree	
Male	34.33%	Incomplete elementary school	0.70%
Female	65.30%	Complete elementary school	0.40%
No answer	0.37%	Incomplete high school	0.40%
Age		Complete high school	7.80%
16 – 22	17.20%	Technician	3.70%
23 – 29	38.80%	Incomplete graduation	26.50%
30 – 39	16.80%	Graduation complete	48.50%
40 – 49	8.20%	Master's	9.70%
50 – 59	13.80%	Doctorate	1.50%
60 +	4.10%	No answer	0.70%
No answer	1.10%		

Of the respondents, 74.6% have lived in Caruaru for more than 10 years and 75% of them are graduates or are undergraduate students. From this and the data in Table 1, there is a strong indication that the respondents have the technical capacity to understand the subject reported here, as well as, know the characteristics of the municipality in question.

3.2 Specific knowledge analysis

Social distancing. An interesting fact was that 89.9% of respondents partially or strongly agree that social distancing is a necessary action in facing the COVID-19, while 82.1% believe that people are not respecting social distancing in Caruaru. They also partially or strongly disagree that economic activities return to normal as long as the virus is not controlled, thus maintaining social distancing as a preventive action.

However, analyzing the relationship of the three variables mentioned above with the respondents' age, Spearman's correlation was performed and it was found that there is a weak correlation in all cases ($r = -0.070, p = 0.254$; $r = 0.108, p = 0.080$ and $r = 0.062, p = 0.311$, respectively).

Cases of the disease and fear of contracting COVID-19. From the 268 respondents, 81.0% stated that they did not show any symptoms of COVID-19 at the time of answering the questionnaire, 15.7% said they had symptoms, but did not take the exam to confirm, while 3.4% took the exam. Of those who took the exam, only 1.5% had the diagnosis of COVID-19 confirmed. Thus 87.3% of respondents claimed to have a moderate to very high fear of contracting COVID-19. Fig.2 shows the intensity of the fear of contracting the disease by age group.

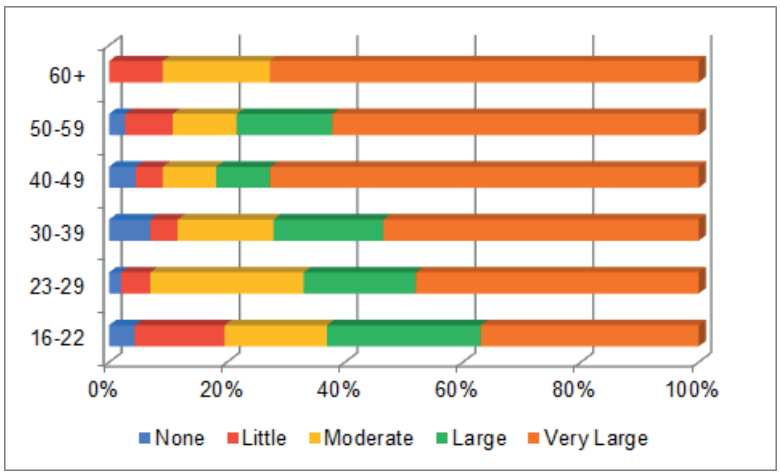

Fig. 2. Fear intensity by age group.

The Kruskal-Wallis test did not detect evidence that there is a difference of fear between the age groups ($p = 0.0889$). The Spearman's correlation also detected a low correlation, almost zero, between age and fear of contracting COVID-19 ($r = 0.024, p = 0.704$).

Reopening of trade. In a scenario of reopening of economic activities in Caruaru, before the development of a vaccine, respondents were asked to evaluate three situations of actions necessary for the reopening of commerce: (a) Use of masks by all people in commerce (employees and customers); (b) Availability and incentive for the use of disinfectants (e.g. 70% alcohol) by all; and (c) Limiting the number of people in the establishment to guarantee social distancing. The results were summarized in Table 2.

Table 2. Necessary actions for the reopening of commerce.

Scale of importance	(a)	(b)	(c)
Strongly important	88,3%	89,1%	87,2%
Partially important	7,9%	7,2%	6,4%
Neutral	0,4%	0,4%	0,4%
Little important	3,4%	3,0%	4,5%
Not important	0,0%	0,4%	1,5%

Therefore, it is noted (see Table 2) that the respondents consider the actions to be very important to enable the return of economic activities. However, there is no statistical evidence that this opinion changes according to the age group. But, a fact that deserves mentioning concerns the strong positive correlation between variables (a) and (b) ($r = 0.782, p = 0.000$) and (a) and (c) ($r = 0.723, p = 0.000$).

This indicates that the people who believe that the use of masks should be mandatory are the same ones who expect the trade to have a more hygienic environment and with restrictions on the number of people. In other words, one action alone does not seem to be sufficient for this sample.

Contagion risk assessment. Respondents were asked to assess the risk of contagion in the following situations (see Table 3):

(d) Public transport without the mandatory face mask;
(e) Public transport with the mandatory face mask;
(f) Attend shopping centers and galleries;
(g) Attend public parks and squares;
(h) Downtown, with busy streets and people without face mask;
(i) Downtown, with busy streets and people wearing face mask;
(j) Contact with close friends or family members who live in the same house;
(k) Contact with people already diagnosed and recovered from COVID-19;
(l) Unprotected contact with people working in hospitals;
(m) Contact with people who work in hospitals with appropriate protections.

Table 3. Contagion risk assessment.

Degree of risk	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)
High	94.8%	19.1%	64.2%	36.3%	87.3%	20.9%	12.4%	22.2%	84.7%	28.0%
Medium	4.5%	63.7%	30.6%	43.1%	9.0%	61.6%	47.2%	30.5%	14.6%	53.7%
Low	0.7%	16.5%	4.9%	18.0%	2.6%	15.3%	36.3%	32.7%	0.0%	17.2%
None	0.0%	0.7%	0.4%	2.6%	1.1%	2.2%	4.1%	14.7%	0.7%	1.1%

Fig.3 shows the contagion risk assessment by age group.

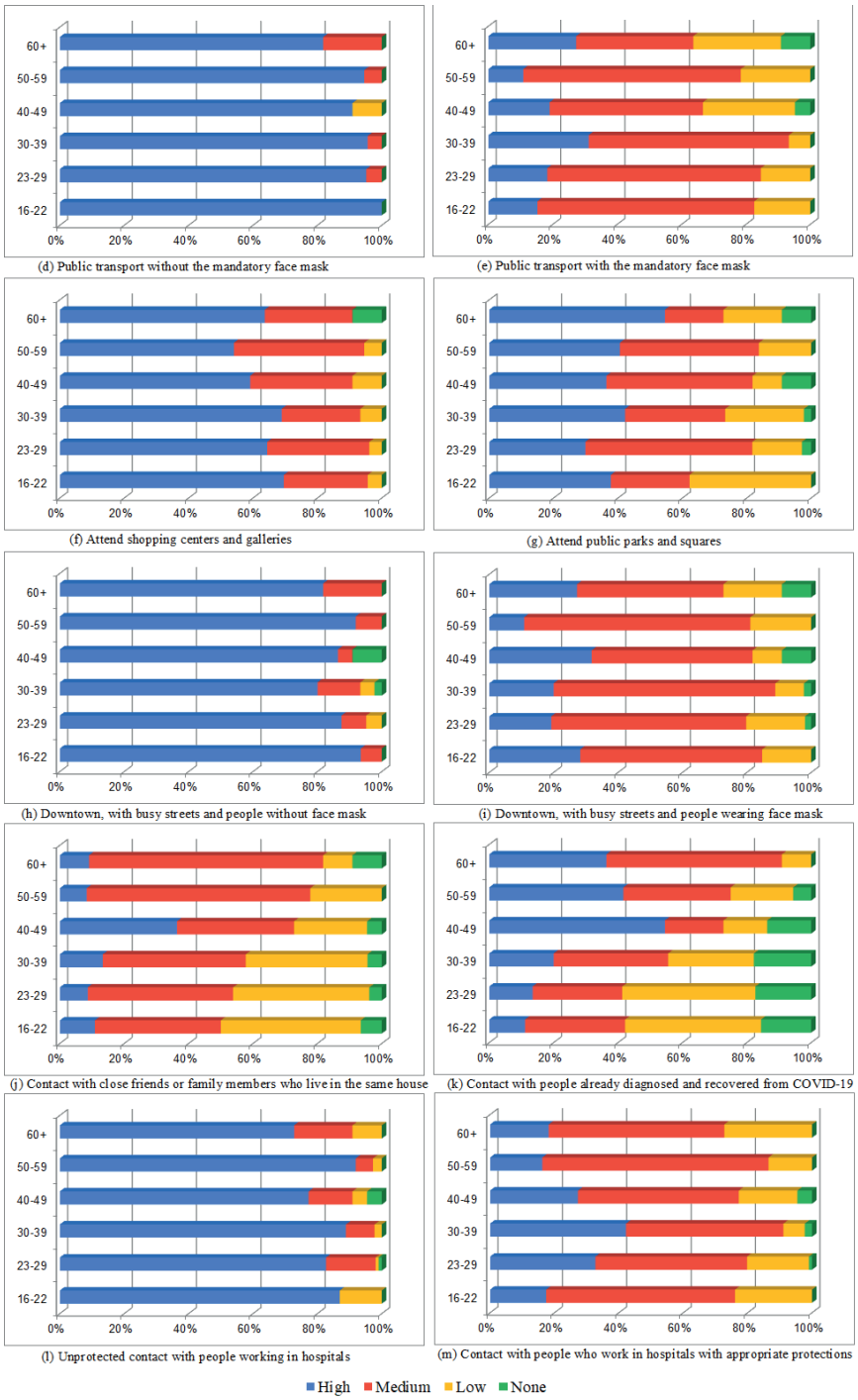

Fig. 3. A contagion risk assessment by age group.

Analyzing Table 3, it can be seen that items (d), (h) and (l) were considered to be at higher risk. Items (d) and (h) are related to overcrowding without adequate Personal Protective Equipment (PPE) and item (l) is related to the proximity of someone more likely to have contact with the disease. Another point is that respondents feel safer with the use of face masks. This fact corroborates the previous statements (Table 2).

The result, using the Kruskal-Wallis test, of the hypothesis that the perception of the risks does not differ between age groups (see Fig.3), and the correlation among age groups and the contagion risks are shown in Table 4.

Table 4. Age group *versus* contagion risks.

Contagion risks	Spearman		Kruskal-Wallis
	r	p	
(d)	-0.150*	0.015	0.450
(e)	-0.063	0.307	0.044
(f)	-0.090	0.144	0.640
(g)	0.071	0.248	0.860
(h)	-0.098	0.111	0.230
(i)	-0.072	0.242	0.500
(j)	0.172**	0.005	0.030
(k)	0.290**	0.000	0.000
(l)	-0.009	0.884	0.338
(m)	0.020	0.746	0.110

*Correlation is significant at the $p<0.05$

** Correlation is significant at the $p<0.01$

Although in all cases the correlation is weak, the Kruskal-Wallis test shows that for statements (e), (j) and (k) the null hypothesis of equality is rejected, i.e., there is statistical evidence that there may be a difference in perception among age groups about some contagion risks.

Knowledge about COVID-19. Finally, some questions were asked to assess the respondent's level of knowledge about COVID-19. The questions were (see Table 5):

(n) My city is hot and is less likely to spread COVID-19.

(o) I have a homemade recipe for flu that helps in the defense of COVID-19.

(p) The use of antibiotics is important in the defense of COVID-19.

(q) I expose myself to the sunlight every day and I absorb sufficient vitamin D in my body. So, I have protection against COVID-19.

(r) I don't trust in information on combating COVID-19 from the local government.

(s) The local recommendations to combat COVID-19 are exaggerated.

(t) Young people have no chance of contracting COVID-19.

(u) Only elderly people die from COVID-19.

Although most respondents disagreed with the statements, it is noted (see Table 5) that the fake news that circulated on social networks, as well as some statements with no scientific basis given by federal public managers, influence the population opinion. Also, 14.2% do not trust the information provided by the municipal public administration and 7.1% believe that the recommendations to combat the virus are exaggerated. Fig.4 presents these data by age group.

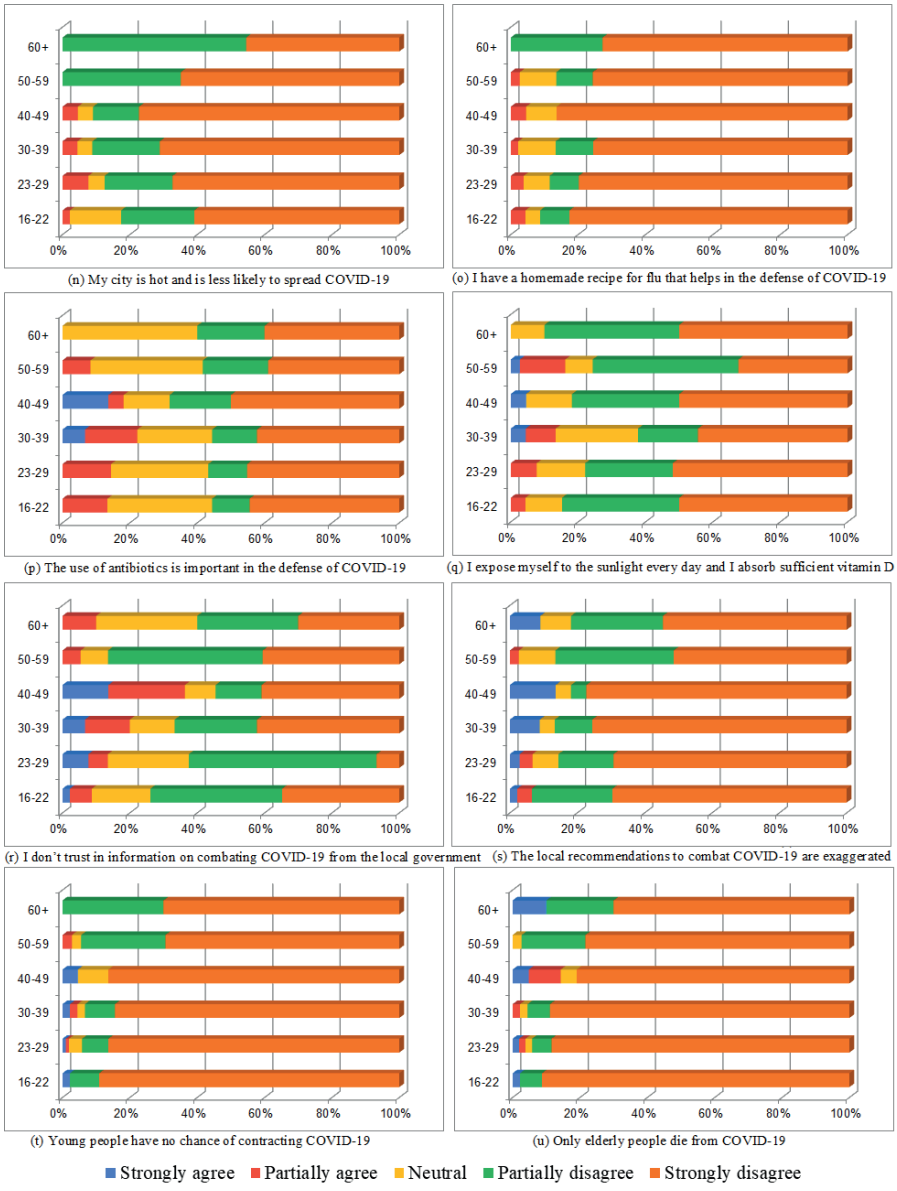

Fig. 4. Respondent's knowledge by age group.

Table 5. Respondents' knowledge

Degree of concordance	(n)	(o)	(p)	(q)	(r)	(s)	(t)	(u)
Strongly agree	2.2%	0.0%	4.5%	1.9%	5.6%	4.5%	1.5%	1.9%
Partially agree	2.2%	3.4%	9.8%	6.7%	8.6%	2.6%	1.1%	1.9%
Neutral	5.6%	7.8%	28.0%	14.6%	10.9%	6.0%	3.0%	1.9%
Partially disagree	23.1%	9.3%	13.6%	29.2%	29.2%	18.7%	10.6%	7.9%
Strongly disagree	66.8%	79.5%	43.9%	47.6%	45.7%	68.3%	83.8%	86.5%

The correlation between the age group and knowledge about COVID-19 is shown in Table 6.

Table 6. Correlations between age range and knowledge about COVID-19.

Respondents' knowledge	Spearman		Kruskal-Wallis
	r	p	
(n)	-0.044	0.474	0.570
(o)	0.050	0.422	0.620
(p)	0.007	0.909	0.890
(q)	0.102	0.097	0.220
(r)	0.032	0.604	0.230
(s)	0.110	0.073	0.320
(t)	0.177**	0.004	0.123
(u)	0.148*	0.016	0.360

*Correlation is significant at the p<0.05
** Correlation is significant at the p<0.01

All correlations were considered weak. The Kruskal-Wallis test does not demonstrate a significant difference in perception among age groups. Analyzing the pairs of alternatives, a strong positive correlation was observed between the variables (t) and (u) ($r = 0.744, p = 000$). In this research, it was observed that people disagree that only elderly people die from COVID-19 and that young people have a chance of contracting the disease, that is, they are dependent variables.

4 Conclusion

This paper presented research about the residents' perception of the Caruaru (PE) city, Brazil. A sample of 268 respondents was reached.

From the analysis of this sample, it can be concluded that the respondents expect that various preventive actions will be adopted by the trade for its reopening (e.g., mandatory use of face masks, constant cleaning, and limiting the number of people). In other words, considering just one action does not seem to be enough.

The results also show that respondents are less afraid of the COVID-19 with the use of Personal Protective Equipment (PPE) as a face mask. This corroborates the statement by [8] that stated campaigns on preventive actions encourage people to increase mobility, i.e., to come out of social distancing.

This result has some limitations. When analyzing the stratified sampling by age group, considering the last Brazilian census in 2010, it was observed that for the age groups of 30 - 39, 40 - 49 and 60 + years the sample was below of the ideal. Another limitation is about the way used to obtain the answer of the population. This limitation does not allow us to extrapolate results for all city, but give us an induction about some COVID problems.

However, it is believe that, for the municipality of Caruaru, the local public administration does not need to link specific awareness campaigns by age group, but needs to be concerned with mitigating fake news. Without clear and immediate actions to refute fake news, the COVID-19 pandemic will be much more challenging [13]. Therefore, the public authorities should increase the population's level of confidence in the information provided by municipal management. This information should be aligned with the recommendations of the World Health Organization.

Acknowledgement

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Computational system for quantitative intra-criterion evaluation in subjective criterion

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Abstract. In general, qualitative intra-criterion evaluation is intuitively based on the decision makers' perceptions and knowledge. In this type of evaluation, commonly, the elicitation process uses semantic scale. This type of scale has a standardized size (e.g., 5 points), and, in many cases, it can be improper. Therefore, this paper presents a computational system based on "play cards" procedure to aid decision makers in the evaluation process in subjective criterion. This allows quantify alternatives based on their rank position, without to establish a standardized size for the scale. The main contribution is assisting decision makers with a user-friendly system in subjective criteria intra-criterion evaluation for multiple criteria subsequent evaluation.

Keywords: Decision Making, Decision support, Preference elicitation, Normalize.

1 Introduction

The decision making is in fact an integral part of everyday life, but it is also a complex activity and potentially of the most controversial, where it need to choose an alternative among a set of alternatives, as well as to choose ways of evaluate them [1]. Complex problems are generally evaluated through a multi-criteria analysis, and decision-maker's preferences are a fundamental input to any Multi-Criteria Decision Aid (MCDA) problem, so their elicitation and representation are obviously important [2].

Thus, when it comes to a multi-criteria model, two types of preferential information can be distinguished [3]: (1) Inter-criteria preferences – judgements refereed to the relative importance addressed to the information carried by each single criterion; and (2) Intra-criterion preferences – judgements refereed to relative values addressed to alternatives, representing different levels of performances in one criterion.

This paper is interested in obtaining intra-criterion preferences. In addition, this paper emphasizes also qualitative evaluation, i.e., subjective criterion, because, in this type of criterion, the decision maker's intuition, based on expertise and experience,

has great relevance due to the lack of quantitative information [4]. Many decision makers have difficulty in evaluating alternatives on subjective criterion.

In this type of evaluation is normal to make use of semantic scales, where decision maker must carry out their evaluations using a pre-defined scale. Nevertheless, this scale size may not be appropriate for decision maker's preferences, or for the set of alternatives. For these reasons, Fontana et al. [5] proposed the use of a procedure, inspired by the work of Simos [6], which uses a 'play cards' to facilitate the quantitative intra-criterion evaluation in subjective criterion. The advantages of this procedure are: (a) it is not tied to a standardized size of scale, and (b) it allows a global visualization of both the order of preference for the alternatives and the intensity of preference between them.

Therefore, since the intra-criterion subjective evaluations are made intuitively, the 'play cards' aim is transcribing this alternatives ranking mental image in order to extract information less complex as possible. Thus, this paper presents a user-friendly computational system to aid decision makers perform 'play cards' procedure to provide intra-criterion information. A normalization process different from [6] is used. This system is able to assist decision makers cognitively, speeding up the evaluation process.

The paper is organized as follows. Section 2 provides a literature overview. Section 3 explains the methodology. Section 4 showed the computational system developed. Finally, section 5 presents some concluding remarks.

2 Literature overview

Preference modelling aims to capturing stakeholder's preferences for the specific decision context. The difficulty here is that preferences cannot be considered as predetermined and stored within human mind. Instead they are modelled during the decision aid process by means of specific techniques, often as a learning procedure, enabling decision makers to think and realise their aspirations [3].

Traditionally, researchers and practitioners agreed that sound decision-making was understood to occur under only the most rational conditions. The ideal decision-maker was understood to be acting from a "cool head". That is, decisions must come from only rational, cognitive processes — emotions have no place in reasoning. Emotions were considered elusive (i.e., not easily understood, much less amenable to empirical research methods) and, thus, unfit to warrant a legitimate position in the quest for understanding ''good'' judgment processes [7].

However, the problem is that one cannot extract emotions and feelings from an understanding of the functions of the mind. Research in the neural processing of decision making reveals that a collection of neural systems dedicated to functions of reasoning and decision making (particularly decisions in personal and social domains) is the same collection of systems involved in emotion and feelings [7-8].

In this way, the measurement system of preferences should be adapted. Measurement is the process by which numbers or symbols are assigned to attributes of entities in the real world in such a way as to characterize the attributes by clearly defined

rules [9]. Thus, measurement requires: entities (objects of interest); attributes (characteristic of entities); and rules (and scales) for assigning values to the attributes [10].

Normally, according to Muravyov and Savolainen [11], the quantitative value (entities and/or attributes) are measured by ratio and/or interval scales (rule), while the qualitative value by ordinal and/or nominal scales, that are also referred to as 'soft' or 'weak' scales. These terms (nominal, ordinal, interval and ratio) are used to describe a hierarchy of measurement scales. Let's assume a scale, s, used to assign real numbers, to a set of elements, A, from observed judgments, so that for all i and j in A, $s(i) > s(j)$ if and only if i is preferred to j. The measure scale can be defined as following [11-13].

Nominal scale (NS) is characterized by some set A and equivalence relation defined on it. In other words 'nominal' scales are merely a ranking, allowing to describe variables or to designate the subject, without recourse to quantification. It is the most elementary level of representation, based on the classification and grouping of elements for the formation of distinct sets. The variables expressed in nominal scale can be compared using only the relations of equality or difference. For example, in Fig.1, there is a set A, where its elements are classified using a nominal scale containing four basic labels: symbols, consonants, vowels and numbers.

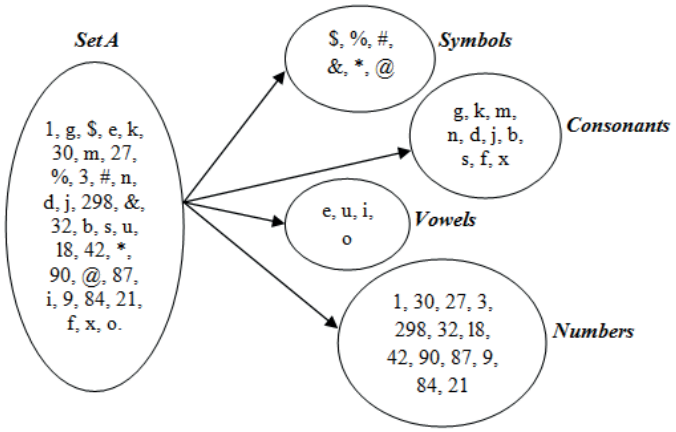

Fig. 1. An example of a nominal scale.

Ordinal scale (OS) is obtained by 'adding' a strict order relation to an equivalence relation on the same set A. Each observation is the association of the individual measured at a given class without quantifies the magnitude of the difference compared to other individuals. For example, in Fig.2, there are five labels (Very bad, Bad, Regular, Good, Very good) that establish an order to preference. Although the order is clear, there is no reference to the magnitude of the difference in preference between labels.

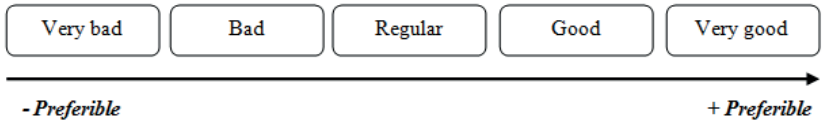

Fig. 2. An example of an ordinal scale.

Interval scale (IS) reaches a "quantitative" form of the previous scale. The zero point on an interval scale is a matter of convention or convenience. This point can be illustrated by two scales of temperature, Centigrade and Fahrenheit (see Fig.3), where there are equal intervals between values and an arbitrary zero is agreed upon for each scale. On these scales, it makes no sense to say that one value is twice or some other proportion greater than another. Interval scales involve a difference (–) instead of order (>) operator, so the set of permissible transformations for interval scales preserves relative differences.

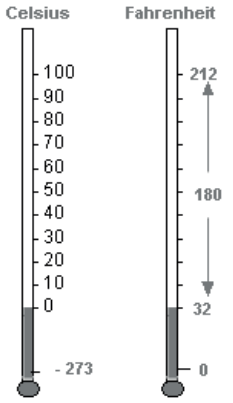

Fig. 3. An example of an interval scale.

Ratio scales (RS) are those most commonly encountered and they are possible only when there are operations for determining all four relations: equality, rank-order, equality of intervals, and equality of ratios. A ratio scale is characterized by a well-defined object whose intensity from natural zero (absolute zero) is the unit of measure. Fig.4 is a good example of a ratio scale that shows a standard of measurement and the zero is clearly the absence of value.



Fig. 4. An example of a ratio scale.

However, some multi-criteria decision methods search facilitate the elicitation process of the decision maker's preferences by using semantic rating scale, considering that the decision maker can be hesitate in assigning quantitative values on differences of attractiveness [14]. The semantic scale consist in a series of rating scales in which the decision maker is asked to give a judgment about something along an ordered dimension, usually of five until nine points, where there are two opposite ends (e.g., strong-week). It is usually used for psychological measures to assess attitudes, beliefs and preferences [15].

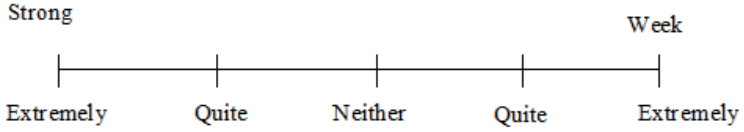

Fig. 5. An example of a semantic scale.

Some authors argue that it is an ordinal scale, others that it is possible to assign values between points, making it an interval scale, especially due to the possibility of assigning a zero point [16]. However, this scale assigns predefined values to the decision maker, and is not appropriate in some cases.

3 Methodology

The computational system developed here was based on the dynamic of 'play cards' from Simos' procedure [6], originally used to establish criteria weights. Thus, Fontana et al. [5] proposed the similar dynamic to evaluate alternatives. Briefly, the decision maker (DM) receives *n* cards of the same size with the name of each alternative and he/she receives others *n* 'white' cards. All cards must have the same size. Then, the DM should rank the cards, with the alternative names, from the worst to the best. However, the system proposed here uses the rank "from the best to the worst", because its visualization seems easier for users.

In the rank, the DM may allocate the same position when they consider the alternatives like the same importance, or insert white cards when they consider the difference between two alternatives subsequent is more than one unit u. Thus, it procedures as follows:

- No 'white' card means that the distance between two alternatives subsequent is equal to one unit *u*,
- One 'white' card means that the difference is twice u, and so on.

Suppose a set *F* with *05* alternatives, $F=\{x_1, x_2, x_3, x_4, x_5\}$, where the DM is requested to rank the alternatives on a certain subjective criterion Cr_1 according to his/her preference. DM should insert white cards always that he/she considers appropriate. Thus, one possible rank is illustrated in Fig.6.

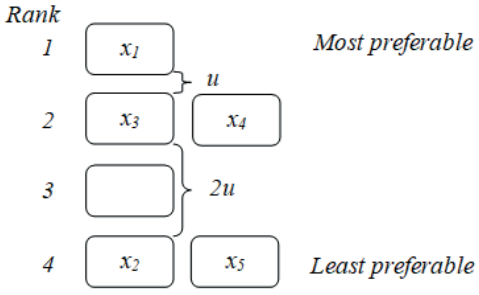

Fig. 6. Illustration of the rank given by DM ('play cards')
Source: Adapted from [17].

To sum up, it can be said that the use of 'play cards' allows to measure the decision maker's preferences through an interval scale. As described earlier, in the interval scale is defined a unit, which will be used in comparison of the alternatives from the difference between two subsequent values. Thus, the ranking visualization facilitates preferences understanding, between the alternatives differences, for DM. Therefore,

the value 'u' represents the difference existing between two subsequent positions in rank. Moreover, it cannot say that the order given by DM represents a value in ratio scale, such as the alternative x_3 is two times more important than the alternative x_2. However, it can say that there is a difference in preference between these alternatives in 2 times 'u' (which is the unit of measure adopted for the difference).

To be more precise, imagine your salary account. Independently on previous months, when you find no money, it means absolute zero (ratio scale). Now, let's considered your preference for fast food on a semantic scale: (-2) Dislike … (-1) … (0) … (+1) ... (+2) Like. The zero value does not characterize lack of taste, only that you neither love nor hate; i.e., zero does not represent absence of value.

Preferences are modeled in a qualitative way because it is hard for humans to give exact numeric values [18]. However, purely qualitative comparisons are not enough in all cases, especially when the primary attributes of interest are quantitative measures, or when outcomes differ in respect to some easily measurable quantity. For example, in standard economic models the utility of money is proportional to the logarithm of the amount of money. Quantitative comparisons also are needed when the decision requires assessing probabilistic expectations, as in maximizing expected utility. Such expectations require cardinal as opposed to ordinal measures of desirability [19].

So, after checking the position of each alternative in rank from 'play cards' procedure, there are some normalization procedures that allow it assign values on a scale, as for example, from 0 to 1. There are basically three normalization procedures, which are [20]:

- Procedure 1: $v'_j(a_i)=v_j(a_i)/[Max\ v_j(a_i)]$, it can be interpreted as a percentage of the maximum value of $v_j(a_i)$. Indicates the distance to the leading alternative.
- Procedure 2: $v'_j(a_i)=[v_j(a_i) - Min\ v_j(a_i)]/[Max\ v_j(a_i) - \text{Min}\ v_j(a_i)]$, it can be interpreted as a percentage of range $\text{Max}\ v_j(a_i) - Min\ v_j(a_i)$. It is observed that zero means only the minimum.
- Procedure 3: $v'_j(a_i)=v_j(a_i)/[\sum_i v_j(a_i)]$, it can be interpreted as a percentage of total $\sum_i v_j(a_i)$.

Proportionality is maintained in procedures 1 and 3 (ratio scale). In the second procedure (interval scale), the proportionality is not maintained, i.e., $v'_j(a_i)/v'_j(a_k)$ is not necessarily equal to $v_j(a_i)/v_j(a_k)$. Simos' procedure used procedure 1 removing the position of the white cards.

However, there is some equivalence on scales when it considers the comparison of each alternative within the same criterion, in assessing intra-criterion. In fact, the ordering of the alternatives for each criterion will be the same for any of the three normalization procedure.

According to Campello de Souza [21], it is possible to transform data that they were recorded in a particular type of numerical scale in another type of scale, since it respect the hierarchy and the basic attributes of each scale. That is, the values provided by the play cards are from an interval scale, it can save them on this scale, or transform them into an ordinal scale, if it is decision maker interest. However, to transform them into a ratio scale, it will require more information from decision makers; such information is not available in this elicitation procedure. Thus, the procedure adopted

for values normalization phase is the procedure 2. Therefore, for the case illustrated in Fig.6, the normalized values, between 0 and 100, are shown in Table 1.

Table 1. Normalized values from Procedure 2

Alternatives	Number of cards	Position	Normalized
x_1	1	1	$v'_i(x_1)=100*([4 - 1]/[4 - 1]) = 100$
x_3, x_4	2	2	$v'_i(x_3)= v'_i(x_4)= 100*([4 - 2]/[4 - 1]) \approx 66{,}67$
White	(1)	3	--------
x_2, x_5	2	4	$v'_i(x_2)=v'_i(x_5)=100*([4 - 4]/[4 - 1]) = 0$

Note that the white card receives no value, since it is interested only in the alternatives, but the position of the white card influences in the outcome of subsequent alternatives. Alternatives in the same position receive the same value.

4 Computational system developed

Computational system was developed in Java (http://www.java.com) and was named by Normalize. Access to the system in: https://sites.ufpe.br/deplog/category/produto-tecnologico/.

The system starts indicating the number of alternatives to be evaluated in the space provided in the top of the screen (see Fig.7). Then the user must click on 'Generate' for the number of suggested alternatives appears on the screen. If the number of alternative is wrong, the user can click on 'Reset' to restart. It should be clear for decision maker that the best alternative should be ranked at the top, i.e., in the first position, then the second best and so on.

Alternatives can be renamed according to the significance given by the DM. Just click once on the alternative and a window will open, which allows name change (see Fig.7). In this window, the DM may also add observations that it will help them in this process.

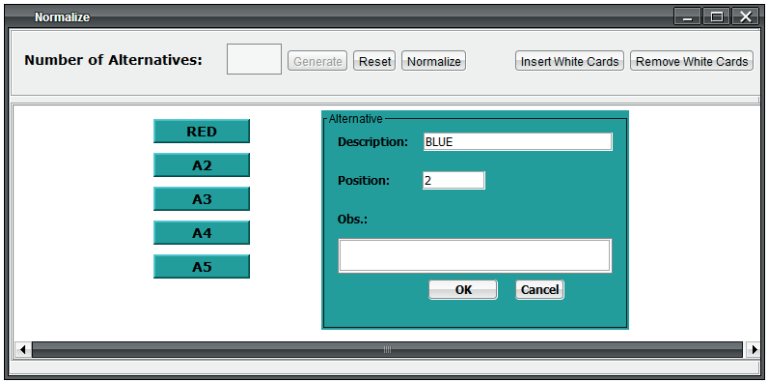

Fig. 7. Rename the alternatives.

After the initial alternatives ranking, the decision maker should ask himself/herself: "Is the distance between subsequent alternative correct?" If 'yes' the DM should click

on ‘normalize’. If ‘no’, the decision maker should insert white cards between the alternatives. For this, the DM should click on "insert white cards" and defines how many white cards want to add after some position. For example: If the DM wants two white cards between the alternatives Red and Blue, which are in positions 1 and 2, respectively, inserts position = 1 and white card = 2, as shown in Fig.8. If the DM added more ‘white cards’ than necessary, the DM can remove them by clicking on ‘Remove white cards’.



Fig. 8. Insert white cards.

At any time, the DM can change the position of the alternatives by clicking on them and modifying the information (position), as well as, if there are alternatives with equally importance, DM should be allocated on the same position. When the ranking of the alternatives satisfies the decision maker’s preferences, the DM should click on ‘normalize’. Then a table will appear with the alternatives, their position in the ranking and their normalized values, as Fig.9.



Alternative	Position	Value
RED	1	100.0
BLACK	4	40.0
BLUE	5	20.0
YELLOW	5	20.0
GREEN	6	0.0

Fig. 9. Normalization procedure.

These values are useful in comparing the intensity of preference between the alternatives. If the DM does not feel satisfied with the values shown in the table (see Fig.9), the DM can click on ‘back’ to return to the same rank (this button will appear in same place than “normalized”) or clicks on ‘reset’ and restart the process. The DM can ‘reset’ at any moment.

5 Conclusion

This paper focused on a very common problem that is the difficulty of decision-makers in evaluating alternatives on subjective criteria. This assessment is usually made intuitively, based on knowledge and experience of own decision maker. In this case, the greater the number of alternatives, the greater is the difficulty to the DM in establishes preference differences between them.

Another common problem is the use of verbal scales fixed for conducting such evaluations, since to quantitatively evaluate an alternative in a qualitative criterion is very difficult to most decision makers. For this reason, commonly, the evaluation is made by a semantic scale and, then, assigns numerical values for each label. In addition, the values range in semantic scale fixed may not be suitable for the decision maker to evaluate the alternatives properly. The ideal values range changes from decision maker to decision maker and hinder their pre-establishment.

Thus, this paper presented a computational system that performs a procedure similar to 'play cards' proposed by Simos [6] to elicit the criteria weights, but it doesn't use the same normalization process. Intuitively the DM ranks the alternatives from best to worst. The easy rank visualization facilitates the DMs to understand their preferences. In this rank, there are not restrictions as to its size, which increases the flexibility of the procedure for preferences elicitation. Each alternative position in the ranking is normalized in an interval scale, thus, the DM can apply some multi-criteria decision making method, for example.

The main contribution of this paper is the computational system developed based on play cards idea to evaluate alternatives under qualitative criteria possibility. This is a user-friendly system and it allows the elicitation procedure to be performed anywhere, with or without a facilitator presence. This system can be used in any multi-criteria problem that involves intra-criterion evaluation in subjective criteria.

This work is not intended to make a final decision. Thus, work's limitation is the fact that the developed system performs only the intra-criterion evaluation and only one criterion at a time. Advances in this system can be made to enable intra-criterion evaluation of multiple criteria, as well as inter-criteria evaluation to assist in final decision making. In addition, despite numerical transformations performed, the resulting scale is interval. Therefore, decision makers must be careful to a possible results' misuse as a ratio scale.

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Mineração de processos e aprendizado de máquina aplicado ao processo de empréstimos pessoais

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Resumo. O processo de empréstimos é essencial para sistemas financeiros. E com a queda dos juros, tal processo ganha espaço. Processos podem ser analisados por meio da mineração de processos, que tem como objetivo a análise a partir de dados sobre a execução do processo, o que permite aprimorá-lo. Assim, esta pesquisa tem como objetivo o uso de técnicas de MP a fim de identificar melhorias para tornar esse processo competitivo em um ambiente mais tecnológico e capaz de atender uma demanda crescente. Inicialmente, foi realizada uma revisão sistemática da literatura para compreender o estado da arte da MP em ambientes financeiros. Na sequência, foi utilizada a técnica PM² a fim de compreender o registro coletado, realizar o seu tratamento, aplicar técnicas de mineração de processos e então propor melhorias. Desse modo, evidenciou-se que a MP, em sistemas bancários, é fortemente proposta junto a outras técnicas como forma de criar sistemas de previsão e identificação de fraudes. Porém, muitas vezes, não são realmente implementadas. Logo, conclui-se que o processo possui muitas oportunidades de melhorias, entre elas o desenvolvimento de técnicas que evitem que os clientes enviem documentos errados, um rearranjo das atividades entre os recursos, a eliminação da atividade "W_Handle_Leads" que não agrega valor. Como trabalhos futuros, propõe-se o desenvolvimento de um sistema de juros de empréstimos mais inteligente baseado em técnicas de aprendizagem de máquina que compreendem critérios mais sensíveis à necessidade e capacidade de pagamento do cliente.

Palavras-chave: Mineração de Processos; Business Process Management; Banco.

1 Introdução

A mineração de processos é uma área de conhecimento emergente que, com um conjunto de ferramentas, promove *insights,* baseados em fatos, que visa descobrir, analisar e melhorar os processos a partir dos dados disponíveis nos registros de eventos de sistemas [1]. Assim, [2], apresentam que 6,4% das aplicações sobre mineração de processos são destinadas a processos financeiros. Dentre tais aplicações um dos destaques é a análise do processo de empréstimos, a qual se refere a tomada de um montante de crédito, geralmente para curto ou médio prazo, por meio de um contrato junto a uma

instituição financeira, com a responsabilidade de pagamento desse valor acrescido de juros em um prazo previamente determinado.

Sua principal vantagem é a facilidade e a rapidez em conseguir o recurso desejado, até mesmo para quem já está com problemas financeiros. Entretanto, um fato histórico relevante é a crise de 2008, a qual foi motivada, essencialmente, por um abuso na concessão de empréstimos [3] o que tornou mais difícil a obtenção de empréstimos. Assim, já que tais operações não geravam mais fluxo de caixa e os bancos perdiam sua liquidez, tal cenário causou uma insegurança no mercado e os investidores passaram a retirar seu investimento de tais fundos. O que demonstrou, o grande impacto que o processo de empréstimos tem na economia e na sociedade.

Dessa forma, mesmo que gerido majoritariamente por bancos [4] a competição com emergentes instituições tecnológicas financeiras (*FinTechs)* é uma crescente ameaça para o setor [5]. Então, com a necessidade de se reinventar, técnicas modernas como modelos de aprendizagem de máquina ganham destaque. Por exemplo, [6]–[8] aplicam modelos de regressão e árvores de decisão direcionados à classificação e identificação de fraudes em sistemas de empréstimos bancários. Neste contexto, este trabalho tem como foco estudar o registro de eventos disponibilizado por uma instituição financeira, o que busca compreender seu processo e sugerir melhorias e aplicar modelos de otimização da análise de crédito para manter a competitividade desse processo no mercado. Além disso, o processo de empréstimo pode ser beneficiado com a utilização de técnicas de aprendizagem de máquina. O uso de técnicas de mineração de dados permite que o processo de negociação a respeito do valor do empréstimo seja acelerado por meio da indicação do valor máximo que pode ser ofertado ao cliente de acordo com as suas características.

2 Trabalhos correlatos

Com o intuito de compreender o estado da arte da mineração de processos, a metodologia de mapeamento sistemático da literatura desenvolvida por [9] foi utilizada. Nesta metodologia cinco etapas são desenvolvidas: (1) realiza-se a definição do escopo da pesquisa; então (2) é conduzida a pesquisa; na sequência (3) executa-se o processo de filtragem e seleção dos artigos coletados; por sua vez (4) é desenvolvido o processo de classificação dos artigos; e por fim (5) é realizado o mapeamento sistemático.

Assim, observa-se que a abordagem da mineração de processos (MP) em instituições do setor financeiro acontece de diversas formas. [10] utilizam a técnica IBUPROFEN de reestruturação destinada a modelos de processos para assegurar a garantia de qualidade nos relatórios de contas bancárias. A técnica proposta tem a função de reduzir as falhas de qualidade. Os autores afirmam que tais questões afetam seriamente a compressibilidade e a capacidade de modificação dos modelos de processos de negócios.

[11] e [12] analisam processos correlatos a *call centers* de bancos e apresentam, respectivamente, uma investigação sobre a duração de atendimentos que utiliza registros de eventos junto da lógica fuzzy a fim de compreender desvios de processo com foco na perspectiva da frequência dos dados e ao levar em conta possíveis flutuações nesse processo; e uma análise que utiliza um algoritmo *fuzzy* em um banco da Tailândia com

o intuito de compreender as interrelações no processo do atendimento ao cliente e quais problemas podem existir no sistema desenvolvido.

Questões que envolvem fraude bancária são analisadas por [6]–[8]. Os autores utilizam a MP como ferramenta auxiliar durante o processo de classificação das fraudes existentes e até mesmo no desenvolvimento de sistemas que colaboram na previsão de novas fraudes. Respectivamente, os autores fazem uma avaliação de fraude em empréstimos ao usar MP junto de analise multicritério (AHP) e lógica *fuzzy* para aumentar a acurácia da avaliação. Os autores identificaram ataques em contas de clientes através do *internet banking* ao utilizar um método de avaliação de fraude baseado em uma classificação por algoritmos de árvore de decisão e *alpha*+++.

Em empréstimos pessoais e cheque especial, além de [6] citado no parágrafo anterior, [13] aplicaram a MP como base para descoberta do processo e análise, e desenvolveram um modelo preditivo usando redes neurais para minimizar a alocação de recursos destinados a essa área. Já [14] implementam a MP, de modo exploratório e guiado, com foco na relação dos produtos de uma ou mais atividades, que visa assim, visualizar, quantificar e compreender a correlação entre as interações das atividades do processo. [15] abordam a aplicação de um modelo de MP de serviço de solicitação de empréstimo em um banco dos Países Baixos e ressaltam, em seu trabalho, como a drástica perca de precisão que a falta de dados gerada nos logs de evento é traduzida no modelo.

3 Etapas da pesquisa

Essa pesquisa, com o intuito de promover uma melhoria à instituição financeira e mantê-la competitiva em meio aos novos desafios do setor, é dividida em quatro etapas, conforme **Fig. 1**.

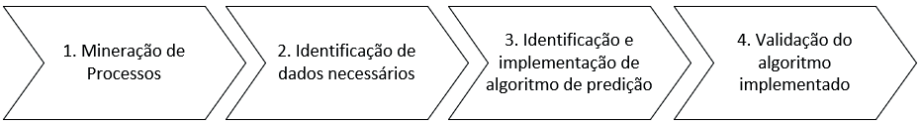

Fig 1. Etapas da pesquisa

Essas etapas compreendem, respectivamente, um projeto de MP que visa permitir uma compreensão do estado real do processo assim como compreender as melhorias que podem ser realizadas de forma pontual. Na etapa seguinte, é realizada a coleta dos dados necessários para a aplicação de algoritmos de aprendizagem de máquina que não estão presentes na primeira etapa, junto a instituição financeira. Após a coleta de dados, a próxima etapa se refere à identificação e implementação do(s) melhor(es) algoritmo(s) de predição para tal caso. E por fim, a validação da implementação e da qualidade do algoritmo junto a instituição. Este artigo refere-se à primeira etapa, a qual se aborda a aplicação da mineração de processos, a fim de identificar as principais características do processo de empréstimo de um banco.

4 PM²: Process Mining Project Methodology

Diversas metodologias foram e ainda são desenvolvidas para a aplicação da MP, tais como Process Diagnostics Method (PDM) de [16], Life-Cycle de [1] e PM²: Process Mining Project Methodology de [17]. Estas metodologias buscam uma otimização e padronização das abordagens dessa tecnologia emergente. A metodologia PM² pode ser descrita como um modelo composto por etapas. De modo que, cada uma dessas etapas possui entradas e saídas. [17] aponta que essas etapas são compostas por "objetos" de objetivos gerais, de dados e modelos. Os objetos dessa metodologia relacionados ao objetivo são *1.Perguntas de pesquisa* (derivadas dos objetivos do projeto); que são encontradas como pergunta inicial do projeto, e *2.Descobertas de performance(ex: gargalos de processo)*; e/ou *3.Descobertas de segurança(ex: inconformidades que identificam fraudes);* que ocorrem nas iterações de análise da mineração de processos, e que assim levam a *4.Ideias de melhoria* que são implementadas na etapa 6. Assim, essa metodologia pode ser organizada em seis etapas conforme **Fig. 2.**

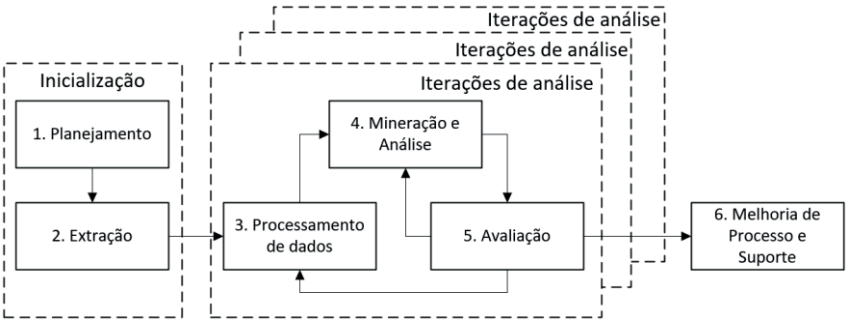

Fig 2. Metodologia PM² - adaptado de [17]

A fase de inicialização contém as etapas 1 e 2, e é composta pelas atividades (a) identificar questões de pesquisa, (b) selecionar processos de negócio, (c) determinação do escopo do projeto e (d) extração dos dados de eventos. Esta etapa tem como input os processos da organização a serem estudados e como saída os dados de evento. Na sequência, tem-se a fase de iterações de análise, compostas pelas etapas 3, 4 e 5. Nesse momento são realizadas, respectivamente, as atividades de (e) criar visões, (f) agregar eventos, (g) enriquecer logs, (h) filtrar logs, (i) descoberta de processos, (j) verificação de conformidade, (k) aprimoramento, (l) análise de processos, (m) diagnosticar, (n) verificar e (o) validar. Esta etapa recebe o *output* da fase anterior e tem como resultado, a elaboração de ideias de melhorias para o processo ou então, se necessário, de novas perguntas para uma nova fase de iteração de análises. Por fim, a etapa 6, refere-se à Melhoria de Processo e Suporte, que possui como entradas as ideias de melhoria da fase anterior e como saídas as modificações no processo. Esta etapa é composta pelas atividades de (p) implementação de melhorias e (q) suporte operacional. Esta etapa visa aplicar o projeto com intuito de modificar a execução do processo real.

5 Estudo de caso

5.1 Inicialização (Planejamento e Extração)

Para a aplicação da mineração de processos foi usada a base de dados, com informações reais e anonimizadas, fornecida por uma instituição financeira. Essa base de dados contém dois registros de eventos (*logs*) de todas as solicitações de empréstimos que aconteceram em 2016 até seu atual *status* em 2 de fevereiro de 2017. A base de dados possui 1202267 registros de eventos que são referentes a 31509 pedidos de empréstimos, bem como um arquivo com todas as 42995 ofertas criadas para esses pedidos. De modo que mais de uma oferta pode acontecer para cada solicitação. Além disso, apresenta 149 recursos (funcionários ou sistema da empresa) que operam em tais processos e atividades organizadas em 3 tipos: A (mudanças de estado da solicitação), O (Mudanças de estado da oferta) e W (eventos de processo). As informações existentes na base de dados são apresentadas na Tabela 1.

Tabela 1. Conteúdo dos logs

Base de dados	Conteúdo
Solicitação	– Valor solicitado (em euro) – (RequestedAmount) – Tipo de solicitação – (ApplicationType) – Motivo da solicitação – (LoanGoal) – Identificador – (ApplicationID)
Oferta	– Valor ofertado – (OfferedAmount) – Retirada Inicial – (FirstWithdrawlAmount) – Número de parcelas – (NumberOfTerms) – Valor da parcela – (MonthlyCost) – Score de crédito do cliente – (CreditScore) – Quem criou a oferta – (Resource) – Se a oferta foi selecionada – (Selected) – Se a oferta foi aceita – (Accepted) – Identificador – (OfferID)

A partir da compreensão do processo que é investigado e de seus elementos, foi realizada a primeira etapa da metodologia PM2, a qual se refere ao desenvolvimento das seguintes questões de pesquisa, que são a base do projeto:

1. Quais são os principais gargalos do processo?
2. Quanto tempo o processo costuma demorar e como isso pode ser melhorado?
3. Quais são os principais desvios do processo padrão? E eles são um problema?
4. Como os processos poderiam ser melhorados?

Por sua vez, as etapas (b) seleção dos processos de negócios, (c) definição do escopo da extração de dados e a (d) extração dos dados de eventos dos sistemas de negócio não serão necessárias, uma vez que essas atividades foram, respectivamente, definidas e ofertadas pela instituição financeira. Dessa forma, como *output* da inicialização, se tem

as perguntas de pesquisa e os dados de eventos para realização de processamento dos dados e mineração.

5.2 Processamento de Dados

Na etapa de processamento de dados, a atividade criação de visões (e) não é necessária, afinal o foco deste projeto é a resolução das questões de pesquisa que visa encontrar potenciais melhorias e não o desenvolvimento de pontos de vistas. Também não é necessária a etapa (f) agregação de eventos, pois tal base já possui os registros de dados na granularidade e exibição necessárias. Porém, a fim de atingir o objetivo dessa pesquisa, os *logs* de ofertas e solicitações foram, (g) enriquecidos e (h) filtrados da seguinte forma:

1. Enriquecimento no *log* das ofertas:

- $Juros = \frac{Customensal * Númerodeparcelas}{ValorOferecido}$

(1) Com essa informação, junto do score de clientes, objetivos da solicitação de empréstimos e valor solicitado é possível analisar as relações das recusas de ofertas de empréstimos;

- $\%Coletado = \frac{ColetaInicial}{ValorOferecido}$

(2) Permite a análise do comportamento do consumidor em relação aos seus objetivos com o empréstimo;

5. Filtros no *log* de solicitações:

- Seleção apenas das variantes compartilhadas por pelo menos onze casos, compondo assim, 80% de todos os casos, 5% das possíveis variantes e 74% dos eventos. Dessa forma, o número de outliers é reduzido, permitindo um maior foco no processo padrão;
- Remoção de variantes com fins de processos marcados nas atividades "A_Pending", "A_validating", "O_Sent (mail and online)", "O_Sent (online only)" e "W_Call after offers". No log de evento todas as solicitações estão marcadas com um estado "*end*" no fim de suas sequências. Assim, estes *cases* não são relevantes para uma análise do processo como um todo, portanto foram excluídos do *log* de evento.

Desse modo, com os filtros aplicados, se tem como *output* dessa etapa o *log* de eventos do processo. O *log* de solicitação de empréstimos passa a ter 44% dos casos e 36% dos eventos em relação ao seu *log* original. Por sua vez, o *log* das ofertas mantém o volume de 100% dos seus casos com adição de outras duas novas colunas de dados.

5.3 Mineração e Análise

Com o *log* de eventos filtrado e enriquecido como input para a fase de mineração e análise, é então possível, primeiramente, a descoberta do processo. Para tal, o software DISCO é utilizado. Assim, com o foco voltado para a compreensão de gargalos e melhorias de processo, foi escolhido a realização de uma análise de granularidade com 100% das atividades e dos caminhos, para compreender em que arcos ou atividades realmente estão os gargalos. Além disso, duas perspectivas foram escolhidas para a descoberta e análise do processo. Primeiramente, em relação à perspectiva de frequência, a medida baseada em casos foi selecionada por apresentar, com um maior grau de significância, o processo mais recorrente. Enquanto que, as medidas absolutas e de repetições máximas apresentariam melhor as medições de retrabalho do processo. Por sua vez, a perspectiva de tempo permite uma compreensão mais realista do processo padrão enquanto que as medidas total e mediana apresentam perspectivas melhores para análises de custo das atividades ao longo do ano e a medida de duração mínima e máxima apresentam os maiores desvios do processo.

Assim, foi possível identificar que tal processo pode ser dividido em quatro subprocessos, e extrair o mesmo para BPMN, conforme a figura a seguir. Primeiramente, o subprocesso de (1) criação da solicitação de empréstimos, seguido pela etapa de (2) negociação, responsável por definir como será o empréstimo com o cliente; então, caso necessário para a etapa de (3) validação, responsável por analisar a documentação enviada pelo cliente, e por fim a etapa de (4) decisão, responsável por definir se tal empréstimo será realizado, conforme **Fig. 3**.

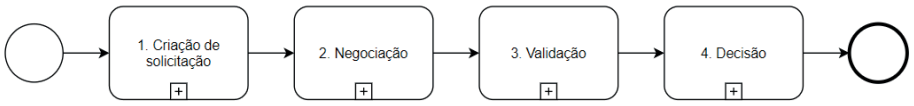

Fig. 3. Diagrama em BPMN do macroprocesso de solicitação de empréstimos

Sendo assim, é importante destacar também que tal processo possui diversos caminhos, e estes podem seguir por variantes com *loops,* que fazem o processo retornar para etapas anteriores, o que gera retrabalho. Então, com o objetivo de tornar a compreensão desse processo mais clara e entender o seu processo padrão, as três variantes mais comuns do processo (menos de 1% das variantes) responsáveis por 34% dos casos e que contêm 25% dos eventos, foram filtradas. Essas variantes de processo foram identificadas pela ferramenta DISCO e então traduzidas para BPMN através do Celonis, conforme a **fig. 4.**

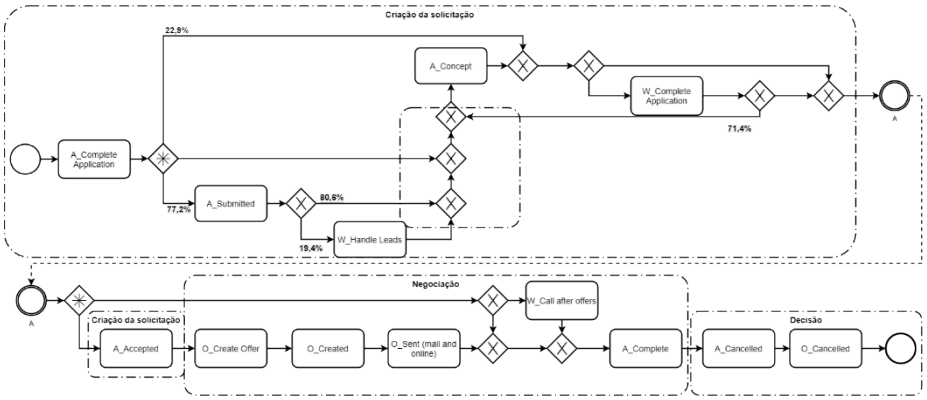

Fig. 4. Principais variantes do processo de solicitação de empréstimos – BPMN

Dessa maneira, é possível compreender que o processo de solicitação de empréstimos bancários, na perspectiva das principais variantes é composto por apenas 3 etapas. Diferente do processo completo, o subprocesso (3) Validação, responsável pela análise de fraudes e de documentos dos clientes, não acontece frequentemente. De modo que, o comportamento mais comum observado inicia com a (1) criação da aplicação ("A_Create Application"), que segue para ("A_submitted") em 77,2% das vezes, de modo que, em 21,2% dos casos realiza-se em paralelo("A_Concept"). Ou então para ("W_Complete Application") em 22,9% das ocorrências. De modo que, quando segue para ("A_submitted"), 19,4% das vezes, o processo passa por ("W_Handle leads") e o restante direciona-se diretamente para ("A_Create_Application"). Na sequência, durante as atividades de ("A_concept") e ("W_Complete Application"), o processo pode se encaminhar de uma atividade para a outra, o que acontece em 71,4% dos casos. Porém, em momento nenhum entra em *loop*, o que indica que acontece somente se necessário, e sem necessidade de retrabalhos. Então, o processo é aceito e passa pela (2) negociação ("A_Accepted" → "O_Create Offer → "O_Created" → "O_Sent (mail and online)"). Na sequência, o processo vai para "W_Call after offers" (o que acontece também em paralelo, em 65% dos casos), e então é (4) finalizado ("A_Complete" → "A_Cancellled" → "O_Canceled").

Sob outra perspectiva, através do uso do Disco, é possível notar que em nenhum dos 5895 casos que o processo padrão compreende houve retrabalhos. Entretanto, é notável que a atividade "W_Handle Leads", que acontece após "A_Submitted", o qual é específico para solicitações que começaram pela internet é utilizada em apenas 15% dos casos. Isso acontece quando alguma falha na avaliação automatizada da solicitação ocorre, o que gera a necessidade da realização de um trabalho manual pelo funcionário do banco.

Outra etapa importante para a compreensão dos processos, é a realização de uma análise descritiva dos dados disponíveis. Para isso, a ferramenta Disco disponibiliza a duração média e a frequência relativa de cada atividade. Assim, referente ao processo de solicitação de empréstimos, é possível notar que, para seu *log,* a maioria dos processos é cancelado. Em números absolutos, existem 39312 atividades somadas de "A_Complete", "A_Cancelled", "O_Cancelled" e "O_Refused". Entretanto existem

apenas 13920 casos. Ou seja, é evidente um número alto de retrabalho durante a negociação do empréstimo. Também, observa-se que 0,15% dos processos terminam como "A_Complete", enquanto que 19,9% terminam como "O_Refused" e 79,48% terminam como "A_Cancelled" ou "O_Cancelled". O que indica assim que mais de 99% das solicitações acabam sendo canceladas ou recusadas. Então, ao comparar a frequência relativa dos casos na base de solicitações de empréstimos, ao se saber que se tem 13920 pedidos de empréstimos criados e 18106 registros da atividade "O_Create Offer" criados, evidencia-se que as atividades da etapa de negociação são as atividades com maior número de retrabalho.

Sob outro prisma, a duração média de cada atividade durante o processo pode ser observada com o intuito de sinalizar as atividades que mais acontecem e/ou se repetem, e as atividades que são gargalos. Assim, é evidente que o subprocesso de validação é o mais longo, principalmente para as atividades do tipo "W". Pode-se destacar a atividade responsável por avaliar potenciais fraudes, que possui duração média de 8 dias e 11 horas, e pode chegar até 37 dias. Porém, tal atividade, acontece em apenas 0,18% dos casos. Em segundo lugar, para o caso de ser necessário ligar em busca de solicitação por documentos faltantes, é gasto em média 1 dia e 20 horas nessa atividade. Tal atividade acontece em 19,4% dos processos, e chegou a repetir em até 3 vezes no mesmo caso. E, em terceiro lugar, a atividade de validação da solicitação, tem uma duração média de 1 dia e uma hora, porém esta acontece em todo *case* que chega nessa etapa. Assim, "W_Validate application" apresenta ser o gargalo mais recorrente e mais importante a ser resolvido. Seguido por "W_Call incomplete files" e "W_Assess potencial fraud", que são atividades menos recorrentes, porém com durações ainda maiores.

Por sua vez, o subprocesso de ofertas, já citado anteriormente como parte do processo de solicitações, tem um *log* de eventos próprio, devido a sua importância. Portanto, permite uma análise específica e isolada de seus elementos. Seu modelo em BPMN é representado na **Fig. 5**.

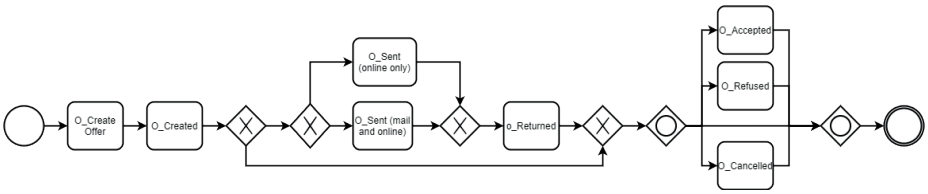

Fig. 5. Diagrama em BPMN do processo de ofertas

Este processo começa com uma criação de oferta ("O_Create Offer" e "O_Created"), que pode se direcionar para ("O_cancelled") ou realiza um processo de envio das ofertas para os clientes, por e-mail e online ("O_Sent (online and mail)") ou somente online ("O_Sent (online only)") e aguardam o retorno ("O_Returned"). Então, as ofertas podem ser canceladas ("O_Cancelled"), aceitas ("O_Accepted") ou recusadas ("O_Refused"). E, então fundamental ressaltar que esse processo possui uma complexidade menor do que o de solicitações, entretanto é mais rico em número em relação a seu conjunto de atributos disponíveis para estudo. Em relação aos gargalos, a análise da frequência relativa das atividades mostra que 88,67% das ofertas são canceladas ou

recusadas, sendo 2,93% logo após a criação da oferta. Além disso, 95% das ofertas são enviadas por e-mail e online, enquanto que apenas 5% são enviadas somente online e 21,5% das ofertas não são respondidas, tendo como última atividade o seu envio.

Também, é fundamental compreender as relações entre as variáveis disponíveis nessas bases, com o intuito de identificar possíveis causas de gargalos e melhorias de processo. Para isso, o software R, que de forma simples permite a análise de informações em grande escala, foi utilizado para realização da análise de correlação das variáveis disponíveis. Dessa forma, a **Fig. 6**, apresenta a correlação entre todas as variáveis.

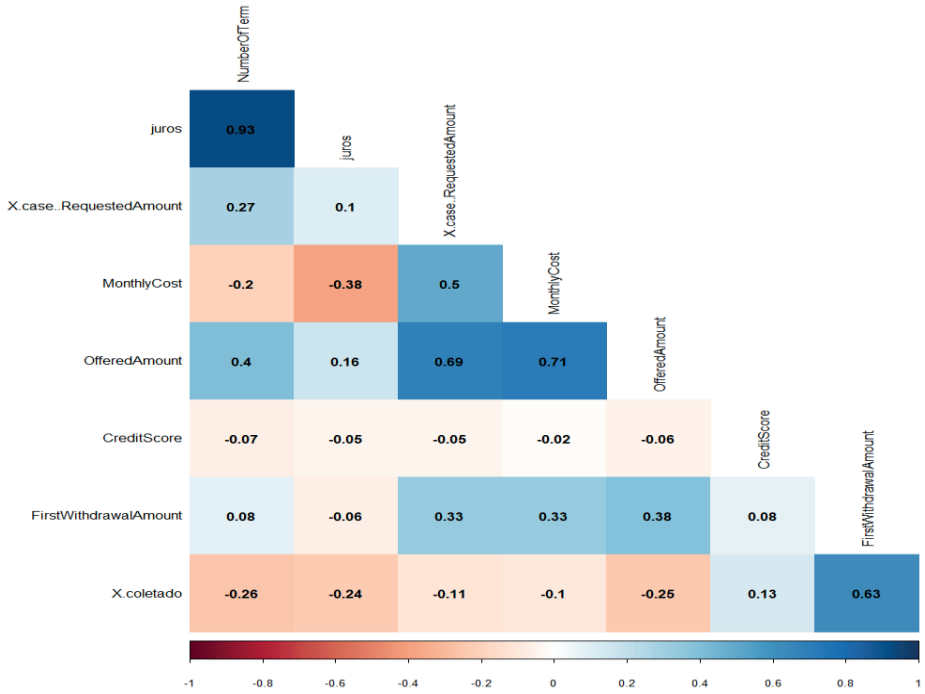

Fig 6. Correlações entre variáveis do registro de ofertas

Assim, é possível observar, primeiramente, que alguns casos como "%¨coletado" e "FirstWithdrawlAmount" não devem ser analisados juntos, pois a informação "% coletado" varia de "FirstWithdrawlAmount". Então, para esse trabalho, a relação do custo mensal e do valor ofertado (correlação mais elevada), foi analisado junto a cada uma das outras variáveis, em forma de gráfico de pontos, e suas observações com o número de parcelas e com o "% coletado" têm destaque. Dessa forma, é possível notar, que os juros aumentam na medida que a relação entre o custo mensal é menor e o valor oferecido aumenta, conforme a **Fig. 7**.

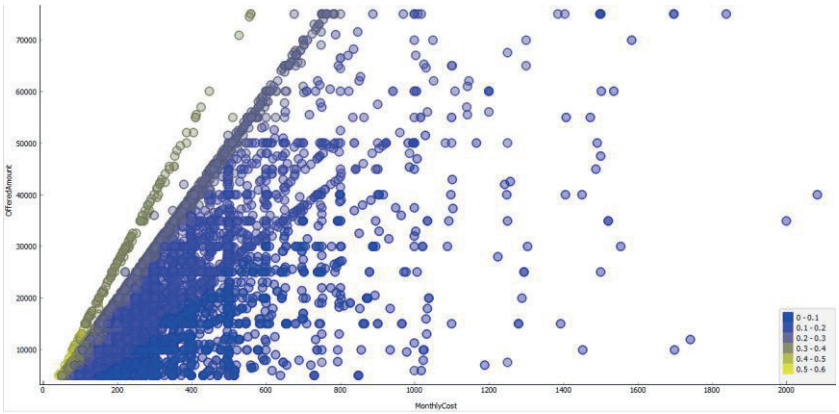

Fig 7. Relação entre custo mensal x Valor ofertado x taxa de juros

Então, nessa etapa é possível identificar como *output* para a etapa de avaliação, as etapas do processo, o que permite a compreensão a respeito do processo, quais são suas variantes e seu processo de comportamento mais comum. Por meio de uma análise descritiva das atividades, quais são as que mais demoram para execução, tanto no sentido absoluto quanto ao se levar em conta sua frequência. Além disso, a taxa de recusa e de aceites das ofertas que tal processo possui, assim como a aceitação das ofertas. E, por fim, compreender a relação entre as variáveis desse processo com o intuito de encontrar formas de melhorar o mesmo.

6 Discussão e considerações finais

Com o intuito de atender ao objetivo da pesquisa, o qual visa identificar, por meio de *logs* de eventos, os gargalos e desvios de um processo de empréstimos bancários e assim poder propor melhorias para tal processo, foi aplicada à metodologia de mineração de processos PM² de [17], no anseio de compreender os *logs* de eventos disponíveis, aplicar métodos de mineração de processos para descobrir os gargalos e desvios do processo e então ser capaz de apresentar sugestões de melhorias. Tal técnica que consiste em 6 fases e tem como objetivo responder à questão de pesquisa, possui as fases (1) planejamento do projeto, (2) extração dos logs, (3) processamento dos dados e (4) mineração e analise, realizadas no capítulo anterior. Por sua vez, a etapa (5) avaliação é desenvolvida nessa sessão e aborda a relação dos resultados da etapa anterior com as questões de mineração de processos levantadas, e dessa forma propõe ideias de melhorias.

Dessa forma, a respeito da questão "*I. Quais são os principais gargalos do processo?",* em relação ao processo geral de solicitação de empréstimos bancários, é notório que as atividades que mais atrasam o processo, quando acontecem, são as atividades relacionadas a validação da solicitação e analise de potencial fraude. Entretanto, a atividade que mais atrasa o processo, caso aconteça, não está presente em 99,8% dos casos. Sendo assim, as atividades que dizem respeito ao ato de ligar para o cliente quando documentos estão em falta e de validar a solicitação com o cliente, ocorrem em respectivamente 19,4% e 100% dos casos, e que pode inclusive ter retrabalhos,

apresentam-se como os principais gargalos desse processo, devido a sua relação entre recorrência e duração. Por sua vez, o *log* de ofertas não apresenta registros sobre os tempos das atividades e não permite uma compreensão estatística relacionada a suas durações.

Já sobre "*II. Quanto tempo o processo costuma demorar e como isso pode ser melhorado?"* A partir do registro de eventos é possível obter inferências em relação a quantidade de eventos que duraram certo período de tempo. Assim, nota-se para o *log* de solicitação de empréstimos uma duração média de 25,6 dias, com uma amplitude de 1,6 até 169 dias, enquanto que a mediana está em 30,8 dias e a maior densidade de casos se concentra entre 30,4 e 32,3 dias com 30,5% dos casos. De modo que, tal processo pode ser melhorado a partir da redução do tempo de espera que tal processo possui, afinal 79,3% dos casos possuem um tempo de espera maior do que 24 horas e 8% possuem um tempo de espera maior do que uma semana útil. O *log* de ofertas não apresenta registros de tempos durações, impossibilitando tal análise.

A questão, "*III. Quais são os principais desvios do processo padrão? E eles são um problema?"* A atividade "W_Handle Leads", acontece em 15% dos casos. Esta, é executada quando o sistema não é capaz de processar a submissão independentemente, fazendo com que um operador necessite lidar manualmente com tal submissão. Portanto, tal atividade é um processo corretivo e deve ser resolvido e eliminado.

Por sua vez, em relação a questão "I*V. Como os processos poderiam ser melhorados?"* as seguintes melhorias são sugeridas:

- A partir da pergunta um, é notável uma melhoria ao garantir que os documentos sejam entregues corretamente. Tal melhoria pode ser realizada a partir da configuração de uma interface de usuário que se preocupe com a experiência do mesmo e que, de forma intuitiva e amigável, oriente o cliente a preencher corretamente os dados necessários para seu tipo específico de solicitação. Além disso, pode contar com *machine learning* para mapeamento de arquivos que valide a qualidade dos anexos inseridos;
- Já, com a pergunta é notável a redução dos tempos de espera com a finalidade de minimizar os gargalos e aumentar o índice de ofertas aceitas por meio de uma realocação das atividades entre os operadores. Afinal, são notórios grandes valores de tempo de espera durante as atividades, e também que os recursos (operadores) não realizam tempos totais de trabalho de forma igualitária.
- A partir da pergunta três, a da exclusão da atividade "W_Handle Leads", que executa um papel puramente corretivo no processo é notável. Esta, pode ser executada a partir de um estudo aprofundado dessa atividade e de suas correlatas.
- Através das **fig. 6 e 7** nota-se a possibilidade do desenvolvimento de um sistema de juros e parcelamento mais flexível e inteligente com algoritmos que permitam avaliações e predições mais completas e sensíveis em relação a capacidade e forma de pagamento que visa maximizar a conversão do número de propostas aceitas.

Portanto, o trabalho realizado apresenta que o processo de empréstimos é essencial para os sistemas financeiros. De modo que, mesmo com o novo desafio do setor,

relacionado a concorrência com as emergentes *FinTechs*. O processo estudado apresenta uma série de potenciais melhorias, conforme citado acima, que podem ajudar a instituição, a qual o *log* pertente, a se manter ou ainda se destacar no mercado. Tais melhorias, que podem ser desde correções de *loops* do processo ou eliminação de atividades desnecessárias e até mesmo desenvolvimento de formas de comunicação mais assertivas com os clientes, são implementadas na sexta e última etapa da mineração de processos, que diz respeito a melhoria de processos. Entretanto, essa etapa não cabe no escopo desse trabalho e, portanto, tais melhorias se direcionam como sugestões de trabalhos futuros.

Assim, como sequência desse trabalho, será necessário a identificação de todas as variáveis coletadas durante a etapa de criação de solicitação e negociação junto a instituição financeira, já que não fornecidas integralmente nesses *logs*. E dessa forma, mapear quais são as variáveis mais capazes de predizerem valores e parcelas que são propostos em empréstimos junto aos clientes. Então, com essa informação, identificar o melhor algoritmo de aprendizagem de máquina, implementa-lo nesse processo, e por fim, realizar uma atividade de validação da qualidade desse projeto junto a instituição financeira

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Optimization models for the tactical planning of the solid waste collection operation: Case study in Colombia

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Abstract. The accelerated growth of the population and the consumption of goods produce a sustained increase in the generation of solid waste. In this paper, we present a case study of a Colombian company dedicated to collection, transportation, and final disposal of solid waste. The associated problem consists of optimizing the fleet and arrival times of the vehicles at the waste unloading destination to reduce possible congestion in the system and avoid collapse inside the discharge facility. The methodology used comprises two stages. The first one consists of a mathematical programming model through which the optimal fleet size is found. In the second stage, a heuristic algorithm is used to sequence the collection micro routes to be carried out by each vehicle during the week. The result obtained reveal a reduction between 10% and 30% of current fleet and sequencing that allows increasing the number of daily trips made by each vehicle.

Keywords: solid waste collection, optimization, heuristic.

1 Introduction

The world generates 2010 million tonnes of solid waste annually, its generation increases as the population growth, economic development is promoted [1], standard of living improves, and consumptions habits change [2]. Solid waste generates from unwanted or discarded materials at the end of its life cycle, comes from domestic, commercial, institutional, and industrial consumption [3]. Waste come mainly from organic matter which represent the highest percentage of generated waste and the remaining fraction comes from metals, glass, plastics, papers [1], leather, rubbers, batteries, textiles, and construction materials [4].

Globally, developed countries are the generators of 34% of waste [5]. Latin America generates on average, one kilogram of solid waste per inhabitant per day representing around 10% of the generation of solid waste worldwide. Colombia generates approximately 6% of this waste, which equals to 12 million tonnes per year. The high generation of these waste and the low level of reusing and recycling of them leads to saturation

in landfills and facilities to dispose and treat them generating a negative impact on the environment and the society [6].

Solid waste management involves the processes of generation, separation and onsite storage, collection, transfer and transport, processing, recovering and final disposal [7]. Collection and transport represent between 60% - 80% of the total cost of solid waste management [8, 9]. These processes include the activities of collecting and transporting solid waste to a destination that may be a landfill, a material processing of treatment facility or waste transfer station (WTS) [2]. Particularly, a WTS is a place within an urban area where the transfer of solid waste of compactor vehicles to others vehicles with greater load capacity is carried out, which are in charge of transporting the waste to the sanitary landfill located on the outskirts of the city.

In the city of Medellín (Colombia) a new WTS will be installed through which the operation of the service can be improved with respect to activities such as the collection, transport, and transfer of solid waste. This brings benefits at an environmental and social level. In addition, this allows the operation to be more efficient generating a reduction in costs. The operation of these facilities depends on the proper management of the municipalities, who oversee generating strategies for proper management and of defining possible areas of location [10].

The WTS generates positive impacts related to the compactor vehicle fleet, such as the reduction in travel times to landfills and unproductive times, at the same time, allowing a reduction in the operating costs [11]. In this order of ideas, this work addresses the case study of a Colombian company dedicated to providing the collection, transportation, and final disposal of solid waste. We present a mathematical programming model to determine the optimal fleet size and a heuristic algorithm built to sequence the micro routes that each vehicle will serve during the week.

The remaining of this paper is structured as follows. Section 2 contains a literature review about applications of operations research and optimization in solid waste collection. Section 3 presents the description and formulation of the mathematical models developed to determine the optimal fleet size and sequence of the collection micro routes. Section 4 also presents a heuristic algorithm to schedule the micro routes. Section 5 presents the results of the case study. Finally, Section 6 concludes and present the major findings of the case study as well as future work opportunities.

2 Literature Review

Operational research has been successfully applied in planning of solid waste collection systems for decision making at the strategic, tactical, and operational levels. In the practice, location models have been used to locate landfills, WTS [12] and containers in residential areas [13]. Additionally, it has been used to take tactical frequency assignment and zoning decisions [14, 15] such as operational routing decisions [16] and personnel assignment [17]. The interested reader is referred to [18] for a recent review focused on the location of facilities (landfills and WTS) and other strategic and tactical decisions (zoning, frequency allocation, fleet composition, etc.). Furthermore, in [8] the authors presented a review focused on the routing of collection vehicles.

In Colombia, operational research has been used for the planning of solid waste collection systems for residential waste, hazardous waste, and recycling. For example, in [19] the location of landfills with potential for future expansion was studied to address the problem caused by the number of landfills that have reached the end of their useful life in Colombia and other emerging countries. Using a multiobjective optimization model, the authors of this work explore the trade-off between operating costs and environmental risk for a Colombian case in the center of the region Valle del Cauca. Similarly, in [20] the location of WTS for the collection of hazardous hospital waste is studied with a bio-objective optimization model that is solved with a genetic algorithm.

Recently, the interest for the use of waste in the framework of circular economy projects such as waste-to-energy or industrial symbiosis has opened new opportunities for the application of optimization models and heuristic solution methods. For example, the one presented in [21] where sugar cane residues are used for energy cogeneration and those presented in [22, 23] that addressed the design of collection routes for the reuse/recycling of residues.

Particularly, to determine the fleet size in the collection of solid waste, the possibility of making multiple trips with the same vehicle in one day arises as an interesting planning option. This characteristic results in the vehicle routing problem with time windows and multiple trips like the one studied in [24]. In this work, the authors initially generate the routes with a vehicle routing problem with time windows and in a second stage they group them into trips made by the same compactor vehicle to minimize the fleet size. Unlike the work presented in [24], in our case, the modification of the collection micro routes is not possible. The only possible modification for these routes is to change the collection day to reduce the number of vehicles needed and better balance the amount of waste collected per day.

Likewise, in [25] the scheduling of waste collection routes was studied in a similar context in which the collection routes are fixed. In a real application carried out in the city of Porto Alegre (Brazil), the aim is to minimize collection costs which include fixed (fleet) and variable costs associated with the routes. Although this problem can be efficiently solved in some cases, the objective of balancing the waste that reaches the transfer and recycling facilities force the authors of this study to resort to heuristic methods inspired on the generalized assignment problem. In our case study, heuristic methods are also used to program the routes on a particular day. However, we considered an (alternative) objective function that has been studied previously in the literature in the so called *truck allocation problem* [8]. This is the minimization of the number of routes that arrive at the WTS in each hour to prevent queuing and the collapse in the internal operation.

In the next section, we describe the two-phase procedure for route scheduling used for the redesign of the solid waste collection operation in the city of Medellín motivated by the entry in operation of a new WTS.

3 Mathematical Model

WTS's allow the discharge of compactor vehicle waste to larger capacity containers or vehicles, this prevents compactor vehicles from traveling to landfills. The introduction of WTS generates a reduction in travel times and an increase in the number of trips that compactors can make to collect waste (known as micro routes in this context). For a city that has defined the micro routes in which the operation is carried out, an implementation of a facility like this leads to a reduction in the vehicle fleet and savings in operating costs. Therefore, through the application of mathematical programming techniques, we developed mathematical models to determinate the optimal size of the compactor vehicle fleet and the sequence of micro routes that must be served by each vehicle during the week.

3.1 Determination of vehicle fleet size

The determination of the fleet size was formulated as a lexicographic bi-objective optimization model, that finds the number of vehicles necessary to provide the service and, additionally, seek to balance the amount of tonnes collected during each day by these compactor vehicles. These objectives were combined lexicographically defining the reduction of the fleet size as a maximum priority objective.

Given a set M = {1,2, …,$|M||$} of micro routes in which the urban solid waste collection service is provided at a given frequency F = {1,2, …,$|F|$}, each element of F represents a possible combinations of days D = {Monday, Tuesday, …,$|D|$} that must be visited. To determine the number of compactor vehicles, the variable Y corresponds to the maximum number of vehicles scheduled in a day. The variable X_{ij} takes the value of one if the micro route $i \in M$ is assigned to a a vehicle at frequency $j \in F$ and zero otherwise. Additionally, the binary variable C_i is equal to one if the micro route $i \in M$ changes frequency in the new planning and zero otherwise. The variable W_k indicates the amount of tonnes of waste collected on day $k \in D$. Finally, variables W_{min} and W_{max} represent the minimum and maximum amount of tonnes of solid waste collected. Using theses variables, the optimization model is formulated as follows:

$$Min \;\; Y + \epsilon(W_{máx} - W_{mín}) \tag{1}$$

Subject to:

$$\sum_{j\in F} X_{ij} = 1 \;\; \forall i \in M \tag{2}$$

$$\sum_{j\in F} n_j X_{ij} = r_i \;\; \forall i \in M \tag{3}$$

$$\frac{1}{dv}\sum_{i\in M}\sum_{j\in F} v_{kj} X_{ij}(d_i + \max[t_i^{ET}, t_i^{BO}] + f_i + tET + tBO) \leq Y \;\; \forall k \in D \tag{4}$$

$$\sum_{i\in M}\sum_{j\in F} tn_i X_{ij} v_{kj} = W_k \;\; \forall k \in D \tag{5}$$

$$W_{min} \leq W_k \leq W_{max} \quad (6)$$

$$C_i \geq 1 - X_{ij} \quad \forall i \in M, j = freq_i \quad (7)$$

$$\sum_{i \in M} C_i \leq mc \quad (8)$$

$$Y \in Z^+ \quad (9)$$

$$X_{ij} \in \{0,1\} \ \forall i \in M, j \in F \quad (10)$$

$$C_i \in \{0,1\} \ \forall i \in M \quad (11)$$

$$W_k > 0 \ \forall k \in D \quad (12)$$

$$W_{min}, W_{max} > 0 \quad (13)$$

The first term of the objective function (1) seeks to minimize the number of compactor vehicles, taking into account that this value will cover all micro routes, while the second part (multiplied by a very small number ϵ) minimizes (lexicographically) the difference between the minimum and maximum tonnes collected throughout the days of the week, so that a balance in the tonnes collected daily is achieved. Constraints in (2) and (3) guarantee that a micro route will only be assigned to a vehicle on a frequency that is compatible and that this frequency in turn will be compatible with the number of weekly collections in which the micro route must be visited (r_i). Expressions (4) ensures that there is sufficient fleet availability to serve all the micro routes, given the start times of the operation in the micro routes (from the WTS t_i^{ET} or the depot of the compactors vehicles t_i^{BO}), the duration of the micro route (d_i), the completion time of the operation (in the WTS f_i or in the depot tBO), the unloading time in the WTS (tET) and the daily availability of the vehicles (dv). Constraints in (5) accumulated each day the tonnes of the micro routes (tn_i) assigned to frequencies that include this specific day of the week (parameter $v_{kj} = 1$). The minimum and maximum amount of waste collected in the week is defined through constraints in (6). Additionally, expressions (7) and (8) count and control the number of micro routes that change in their frequency (with a maximum value mc), taking into account that they can only be changed for those that include the same number of weekly visits (n_j) in constraints (3) and considering the current assignment of each micro route ($freq$). Finally, expressions (9), (10), (11), (12), (13) define the domain of the decision variables.

3.2 Micro route sequencing

In this work micro route sequencing is understood as the assignment and scheduling of the micro routes to be carried out by vehicles in such a way that their arrival at the WTS to discharge the waste is balanced during the day. Therefore, a second optimization model was developed to make decisions regarding the time at which each micro route will be carried out and to define which of the vehicles will carry it out.

Along this line, the objective function is responsible for minimizing the number of compactor vehicles that arrive at the WTS each hour of the day. In this model, variables

T_{iv} and F_{iv} indicate the hours in which the vehicle $v \in V$ starts and ends the collection in the micro route, respectively. The binary variable L_{ih} takes the value of one if the collection of the micro route $i \in M$ ends in the hour $h \in H$ and zero otherwise. The variable S_{iv}, also binary, takes the value of one if the vehicle $v \in V$ performs the micro route $i \in M$ and zero when it does not. Furthermore, the binary variable P_{im} indicates if the vehicle $v \in V$ performs the micro route $i \in M$ before the micro route $m \in M$ ($P_{im} = 1$), and ($P_{im} = 0$) if not. Finally, the variable Nr refers to the maximum number of micro routes completed in one hour of the day. The following optimization model (inspired by parallel machine sequencing [26]) was formulated for micro route sequencing using the above described variables.

$$Min\ Nr \tag{14}$$

Subject to:

$$\sum_{v \in V} S_{iv} = 1 \ \ \forall i \in M \tag{15}$$

$$\sum_{i \in M} S_{iv} \leq rm \ \ \forall v \in V \tag{16}$$

$$S_{iv} \sum_{z \in Z} hi_z \, zn_{iz} \leq T_{iv} \ \ \forall i \in M, v \in V \tag{17}$$

$$S_{iv} \sum_{z \in Z} hf_z \, zn_{iz} \geq T_{iv} + \max[t_i^{ET}, t_i^{BO}] + d_i \ \ \forall i \in M, v \in V \tag{18}$$

$$F_{iv} = T_{iv} + d_i + \max[t_i^{ET}, t_i^{BO}] + f_i + tET \tag{19}$$

$$F_{iv} \leq L_{ih} hd \ \ \forall i \in M, v \in V, h \in H \tag{20}$$

$$\sum_{i \in M} L_{ih} \leq Nr \ \ \forall h \in H \tag{21}$$

$$F_{iv} \leq T_{mv} + K(1 - P_{im}) \ \forall i \in M,\ m \in M,\ v \in V \mid i \neq m \tag{22}$$

$$F_{mv} \leq T_{iv} + KP_{im} \ \forall i \in M,\ m \in M,\ v \in V \mid i \neq m \tag{23}$$

$$\sum_{i \in M} (d_i + \max[t_i^{ET}, t_i^{BO}] + f_i + tET) S_{iv} + ntBO \leq dv \ \ \forall v \in V \tag{24}$$

$$Nr \geq 0 \tag{25}$$

$$T_{iv}, F_{iv} \geq 0 \ \ \forall i \in M, v \in V \tag{26}$$

$$L_{ih} \in \{0,1\} \ \ \forall i \in M, h \in H \tag{27}$$

$$S_{iv} \in \{0,1\} \ \ \forall i \in M, v \in V \tag{28}$$

$$P_{im} \in \{0,1\} \ \ \forall i \in M, m \in M \tag{29}$$

The objective function (14) minimizes the number of routes that are completed at any hour of the day. Subject to constraints (15) that guarantee that a micro route is only assigned to one vehicle. During the day, a compactor vehicle may have assigned at most rm micro routes, which is ensured by expressions (16), these micro routes must be completed in the available operating time for the vehicles, the remaining time is dedicated to preventive maintenance. The group of constraints (17) and (18) ensure thar the

operation of the micro routes is carried out within the time windows (with start time hi_z and end time hf_z) established for the zone to which they belong (zn_{iz}=1). Expressions in (19) relates the variables corresponding to the time when a vehicle starts and ends the micro route, this indicates that a vehicle ends a micro route when it performs the collection operation and makes the respective discharge in the WTS of the solid waste that was collected. Likewise, constraints (20) and (21) count and control the termination of micro routes and indicate that the time at which a vehicle ends a micro route must not exceed twenty four hours a day (hd). Expressions (22) and (23) guarantee that two micro routes will not be programmed at the same time for the same vehicle, each vehicle is in charge of starting a micro route and completing it in order to start the collection in the next micro route, to ensure this these constraints include a large real number K to ensure that only one of the constraints is activated. The time that a compactor vehicle can operate during the day is given by constraints in (24), which considers the operating times in the micro routes, the discharge of solid waste at the WTS at the end of each working duty (carried out twice a two day to change the crew of the compactor, which means that two trips are made to the depot $ntBO$). Finally, expressions (25), (26), (27), (28) and (29) define the domain of the decision variables.

4 Sequencing heuristic

Given the number of micro routes programmed per day (more than 100) and the number of compactor vehicles involved in the operation (between 80 and 103), the direct use of model (14) – (29) is not possible. In particular, given the complexity of the model to assign the micro routes (mainly the time windows of zones and the daily availability of the vehicles), a commercial optimizer was not able to find a feasible solution in reasonable times.

Therefore, for the scheduling of the micro routes that the vehicles must perform every day, a heuristic algorithm was developed under the logic of the parallel machine sequencing problem [26], composed of a randomized construction phase and an improvement phase that tries to balance the number of routes that finish at each hour of the day. The implementation of the two phases assigns the micro routes to the vehicles in such a way as to balance their arrival at the unloading facilities (WTS) in order to avoid congestion that may be generated inside this facility. The randomized construction phase consists of assigning the micro routes to the vehicles, considering the possible routes that it can take. For this case study, in a duty, a compactor vehicle can perform two routes. The first has as its starting point the depot, which is the place where these compactors start and end the operation. The second route departs from the WTS, this is carried out only if the vehicle has made its first micro route and has the possibility of making a second route without exceeding the working day. The general flow diagram of this phase is shown in Fig. 1.

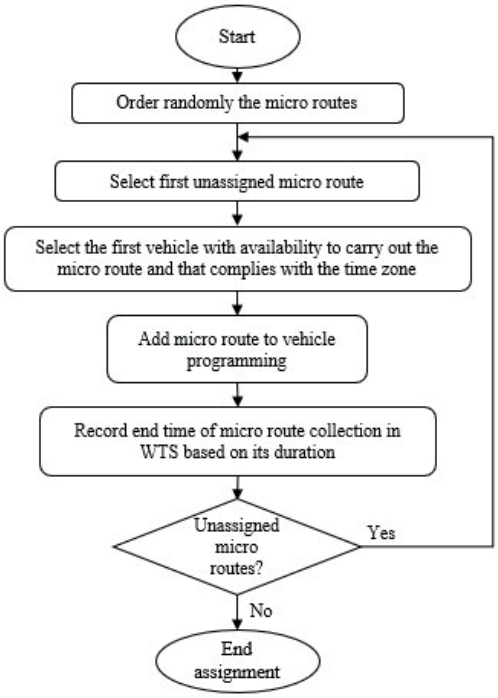

Fig. 1. General scheme of the randomized construction phase for the allocation of the micro routes to the compactor vehicles.

The improvement phase aims at achieving a better balance in the arrival of vehicles at the WTS, the objective is to minimize the number of vehicles that arrive per hour at the facility. Through the local search moves *change of start time* in the collection of the micro routes and *exchange of the visit order* in the micro routes of the same vehicle, the results obtained in the construction phase are improved, that is, a better balance is obtained. Taking the number of vehicles that arrive per hour at the WTS, the improvement phase is performed if an improving solution is found. Within these two moves, the change of start time move analyzes systematically the effect of displacing (in up to three 30 minutes steps forward or backward) the start time of the first route of each compactor vehicle that is involved in the critical time zone (i.e., $h^* = argmax_{h\in H}\{\sum_{i\in M} L_{ih}\}$, the one that determines the maximum number of vehicles that enter the WTS at a given time). When this first move fails to improve the solution, *the move exchange of the visit order* systematically exchanges the order of the micro routes of vehicles arriving in the critical time zone to search for further improvements.

The improvement phase ends when a local optimum is found, that is, and improved result that reduces the number of vehicles arriving per hour at the WTS and none of the two moves is able to improve it further (i.e., a local optimum for the two improvement procedures). When finished, the best balance obtained with the heuristic is reported. This phase is shown in Fig. 2.

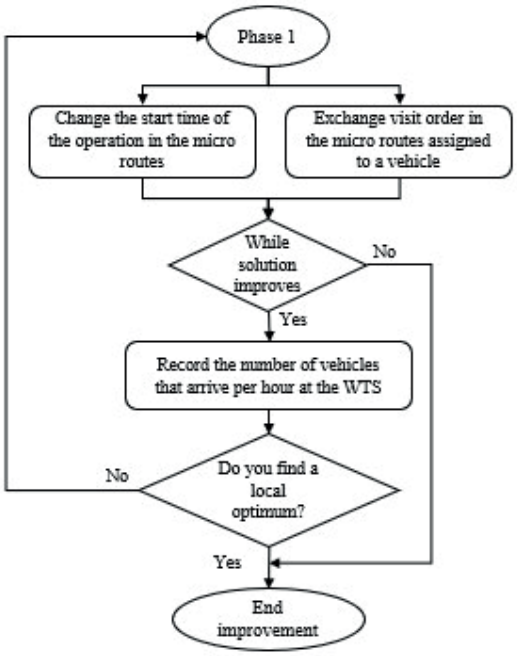

Fig. 2. General scheme of the improvement phase in the balance the arrival of compactor vehicles to the WTS.

5 Results

The proposed mathematical models were implemented in the Xpress Optimization Software using its Mosel Language. The data used come from the historical records of a Colombian company dedicated to the collection and treatment of solid waste, these data were recorded between 2019 and 2020. The results obtained for both models include the projection of growth of the tonnes of solid waste generated in the city for the period 2023 to 2038.

The heuristic procedure for the assignment of micro routes and to balance the arrival of compactor vehicles at the WTS, was implemented in Visual Basic for Applications (VBA) for Excel [27]. To evaluate the performance inside the new WTS using the determined compactor vehicle fleet size and the proposed micro routes scheduling, we used a discrete event simulation model implemented in the Flexsim Software.

Through the model developed to determine the optimal fleet size that considers the effective operating times of the vehicles during the collection of solid waste, we obtained a reduction in the number of compactor vehicles between 10% and 30% with respect to the fleet that currently is under operation. This reduction is due to the decrease in time (about 40%) dedicated to the transport of solid waste with the new WTS. Being closer to the micro routes when unloading waste, allows compactor vehicles to carry out more trips during the day compared to those performed today to the landfill

without the WTS. Fig. 3 illustrates the number of compactor vehicles that are necessary to carry out the collection in the micro routes in the years following the startup of the WTS and considering the projected volumes of solid waste for these years. This quantity considers the fleet with which the micro routes scheduling was performed by the heuristic procedure for model (14) – (29). In some cases, more vehicles were used when compared to those found with the initial mathematical model (1) – (13). Time windows constraints in the zones of the city made not possible to program all the micro routes with the initially determined fleet size. For instance, to ensure feasibility of the second model an increase of 4% of the initial fleet size was needed for the first projected year.

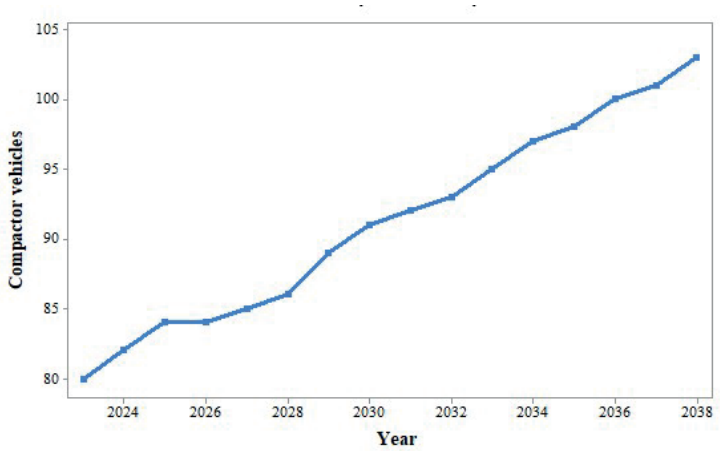

Fig. 3. Compactor vehicle fleet size projection.

When considering a change in the frequencies of the micro routes, a better balance of the tonnes collected daily was obtained. With only a 10% change in frequency of the micro routes, a difference of less than one tonne of collected waste is achieved between the days of the week (i.e., the difference between the day of greatest collection and the day of least collection). It should be noted that in the initial situation (with current frequencies) this range is 121 tonnes. The better balance of the collected waste brings a 4% reduction in the fleet size.

The results obtained with the heuristic for the first projected year, in which the WTS will have started its operation, will be discussed. With the first phase, corresponding to the randomized construction, the arrival of vehicles at the WTS are represented in Fig. 4. The critical hour occurs in the afternoon, in which 29 vehicles finish 12.3% of the micro routes and enter the WTS to carry out the respective discharge of solid waste, during this hour the queue generated inside the WTS increases since all vehicles go through internal unloading operations in which only one vehicle at a time is allowed. With the implementation of the first randomized construction phase, approximately 17% of vehicles can carry out between one and two micro routes per day. For the operation in the new WTS, it is not profitable to operate a vehicle to make only one or two trips as they are currently used to transport and unload solid waste in a landfill located outside the city. However, in the results obtained we show that the randomization of

the micro routes is an influencing factor in the allocation and may be one of the reasons why some vehicles do not reach more than two micro routes. In this case it is ideal, that they can complete up to four micro routes daily. This objective is achieved after the improvement phase.

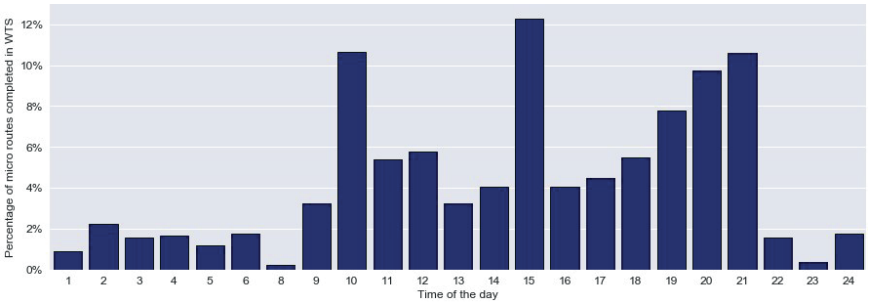

Fig. 4. Behavior in the arrival of compactor vehicles to the WTS after the collection of waste in the micro routes under the application of the randomized construction phase.

By implementing both phases of the heuristic, the results indicate that 6.5% of the vehicles will carry out only two micro routes a day and the remaining percentage will be in charge of collecting solid waste for three or four micro routes. This indicates that approximately 94% of vehicles will collect between three and four micro routes daily. Under this scenario, the percentage of vehicles arriving at the WTS at the critical hour decreases by approximately 14%. In Fig. 5, the result obtained with the implementation of the two phases of the heuristic can be seen, in this case, for the critical hour, the vehicles discharge (on average) the waste of 10.3% of the micro routes served daily.

The comparison of figures 4 and 5, reveals that by means of the randomized assignment and the improvements phase implemented in the heuristic, it was possible to obtain a better balance in the arrival of vehicles at the WTS at critical times. Furthermore, with the reduction in arrival times at the new facility the vehicles have a greater use since they perform a greater number of micro routes that exceeds the trips currently made by each compactor.

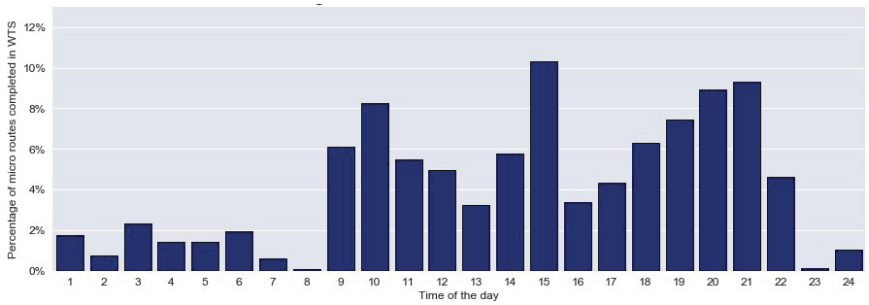

Fig. 5. Behavior of the arrival of compactor vehicles at the WTS after the collection of waste in the micro routes under the application of the randomized construction and improvement phases.

The use of a discrete event simulation model made it possible to evaluate the performance inside the facility, considering the best balance of vehicle arrival at the WTS. For this facility to be operationally viable, in addition to the arrival of vehicles, come other elements must be taken into account: the waste discharge points, the amount of resources for internal and external use to transport the waste to the landfill, the parking slots for these resources and defined locations for scales, porter's lodge and other necessary spaces for the operation.

Different scenarios were proposed considering the variation of the resources that will be used in the WTS. Table 1 shows the results obtained from this variation. The queue analyzed corresponds to the one formed before the entrance scale for the compactor vehicles, this is a critical queue and its formation depends on the availability of unloading points, trailers and internal trucks, if at a given moment none is available or the scale is busy, a queue will begin to form inside the WTS.

Trailers	External trucks	Internal trucks	Compactor vehicles			
			Maximum queue	Average queue	Average time in queue (minutes)	Average time in WTS (minutes)
21	18	4	35	3	20	40
29	18	4	18	2	15	35
35	20	5	12	0.5	2	23
40	20	5	12	0.17	2	22

Table 1. Simulation results.

For the case study, the different scenarios and the capacity of the future facility were analyzed to determine the amount of resources required. Due to the queues allowed in the system, we determined that the continuous operation of the WTS requires 35 trailers and for these vehicles the corresponding parking slots should be considered since they have to wait while they pass to the unloading points.

6 Conclusions

In this paper we present the mathematical models developed to support the tactical decision making of the solid waste collection and transportation operation by a Colombian company. The first mathematical model determines the optimal fleet size of the compactor vehicle to cover the total number of micro routes in the years following the entry into operation of a new WTS. The second model was developed to schedule the service of micro routes during the working week. However, due to its complexity, it was not possible to find a feasible solution with a commercial optimizer in a reasonable time for this model. Therefore, the scheduling of the micro routes was performed using a heuristic algorithm composed of two phases. The first phase consists of a randomized construction heuristic that assigns micro routes to the compactor vehicle while keeping the time windows of the zones and the available operating hours of the vehicles. The second phase improve the initial assignment in order to balance the arrival of vehicles at the WTS using two moves (that change of start time of the micro routes of a vehicle or exchange the order in which they are performed).

Through the application of these models, a reduction between 10% and 30% of the vehicle fleet was obtained for the projected years (years following the entry in operation of the WTS) with respected to the fleet size that the company operates currently. In our scenarios of analysis, these compactor vehicles manage to cover all the micro routes and more than 90% carry out between three and four micro routes daily.

A future study could consider the routing of compactor vehicles in such a way as to reduce the times of completion of the micro routes and, therefore, reduce the fleet size. Likewise, the effect of the change in the frequencies of the micro routes could be considered to know its impact on the programming of the micro routes and on the determination of the fleet size. Furthermore, the scheduling of working hours for the crews of the vehicles could be included in the assignment of micro routes to vehicles. This to better include the labor legislation that regulates the assignment of personnel to the operation and their well-being.

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Prediction of Viscoelastic Behavior of LDPE Produced in High-Pressure Tubular Reactors

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Abstract. We applied a modeling tool for linking molecular architecture of low-density polyethylene produced in high-pressure tubular reactors to linear viscoelastic behavior. The modeling approach applies a rheological model based on the reptation theory to connect molecular structure, in terms of molecular weight distribution, to the shear viscosity flow curve. The model is validated against experimental data of low-density polyethylene produced in an industrial reactor.

Keywords: Low-Density Polyethylene, Tubular Reactor, Rheology, Mathematical Model.

1 Introduction

Low-density polyethylene (LDPE) is widely used in many modern applications due to its versatile end-use properties. One of the most widely used production technologies is radical polymerization in high-pressure tubular reactors. This polymerization process produces polymer chains with a relatively broad molecular weight distribution (MWD) and many branches, both long (LCB) and short (SCB). The characterization of the polymer molecular structure helps industrial practitioners find its correlation with the process operating conditions, such as temperature or pressure. Furthermore, it has been established that the chain microstructure controls the end-use properties of polyolefins, including their rheological behavior. Taking advantage of this fact, different grades of LDPE can be obtained, each of which may be engineered to meet special processing and end-use needs.

Linear viscoelastic parameters, such as the relaxation modulus (G), dynamic moduli (G', G'') and the complex viscosity (η^*) are commonly used to characterize polymer melts. They are measured under low-frequency rotational tests, which ensures that the rheological response is due only to the molecular architecture of the polymer. de Gennes [1] and Doi and Edwards [2] where the first to propose a detailed molecular model for predicting these rheological properties for well entangled linear polymer melts in terms of the MWD. The theory of double reptation of Tsenoglou [3] and des

Cloizeaux [4] is usually applied together with reptation concepts. This last author proposed a model called time-dependent diffusion reptation (TDD). Several authors have used the TDD model in conjunction with a double reptation (DR) model obtaining excellent results for linear and slightly branched polyethylene [5].

In this work, the MWD of LDPE produced in a high-pressure tubular reactor, obtained from a high-fidelity reactor model previously developed by the authors [6], was used as input for a rheological model which applies the TDD with DR model. Parameters of the rheological model were fitted against experimental data of the rheological properties. Close agreement with the experimental information was obtained, showing that these models may be extended to polymers with higher levels of branching.

2 Rheological Model

According to the TDD with DR model, the relaxation modulus $G(t)$ of a well entangled linear polymer melt can be estimated as the contribution of a reptation modulus $G_{Rept}(t)$ and a Rouse modulus $G_{Rouse}(t)$:

$$G(t) = G_{Rept}(t) + G_{Rouse}(t) \tag{1}$$

The first one is related to the MWD through the following mixing rule, which weights contributions from various chain lengths and their mutual interactions:

$$G_{Rept}(t) = G_N^0 \left(\int_{Me}^{\infty} \left[F_{TDD}(t,M) \right]^{1/\beta} w(M) dM \right)^{\beta} \tag{2}$$

In this equation, G_N^0 is the plateau modulus, $w(M)$ is the weight fraction of chains having molecular weight M, Me is the molecular weight between entanglements, and F_{TDD} is the relaxation function of polymer chains of molecular weight M in the melt at time t. Exponent β was set to 2 according to the double reptation theory [3]. According to the TDD model, function F_{TDD} is defined as:

$$F_{TDD}(t,M) = \left(\frac{8}{\pi^2} \sum_{p\ odd} \frac{1}{p^2} \exp\left(-p^2 U(t,M)\right) \right)^{\beta} \tag{3}$$

Function $U(t,M)$ in this equation consists of two terms: the first one represents relaxation by reptation as expressed previously by Doi and Edwards [2], the second one represents contributions by fluctuations of the tube length around its equilibrium value.

$$U(t,M) = \frac{t}{\tau_{rept}} + \frac{M^*}{M} g\left(\frac{M\ t}{M^*\ \tau_{rept}} \right) \tag{4}$$

$$g\left(\frac{M\ t}{M^*\tau_{rept}} \right) = -\left(\frac{M\ t}{M^*\tau_{rept}} \right) + \left(\frac{M\ t}{M^*\tau_{rept}} \right)^{0.5} \left[\left(\frac{M\ t}{M^*\tau_{rept}} \right) + \left(\pi \left(\frac{M\ t}{M^*\tau_{rept}} \right) \right)^{0.5} + \pi \right]^{0.5} \tag{5}$$

$$\tau_{rept} = K_{rept} M^3 \tag{6}$$

When M is below Me, the relaxation process occurs through monomer friction and is described by the Rouse mechanism. For entangled polymers with $M > Me$, relaxation processes that are faster than the reptation time are also described by the Rouse process. This is represented by:

$$F_{Rouse}(t,M) = \sum_{p=N}^{\infty} \frac{1}{N} \exp\left(\frac{-p^2 t}{\tau_{Rouse}(M)}\right) + \frac{1}{3}\sum_{p=1}^{N} \frac{1}{N} \exp\left(\frac{-p^2 t}{\tau_{Rouse}(M)}\right) \quad (7)$$

$$\tau_{Rouse} = K_{Rouse} M^2 \quad (8)$$

Here $N = M/M_e$ is the number of entanglements per chain. The Rouse modulus is then obtained using a linear mixing rule:

$$G_{Rouse}(t) = G_N^0 \left(\int_{Me}^{\infty} F_{Rouse}(t,M) w(M) dM \right) \quad (9)$$

Once the relaxation modulus of the melt is estimated through eq. (1), it is used to predict the storage and loss moduli G' and G'' employing the Schwarzl [7] relations. Finally, the complex viscosity η^* is estimated as a function of the frequency ω ($\omega = 1/t$):

$$\left|\eta^*(\omega)\right| = \frac{1}{\omega}\left(G'(\omega)^2 + G''(\omega)^2\right)^{1/2} \quad (10)$$

The polymer molecular structure input for the rheological model is the MWD ($w(M)$). The rheological model involves three parameters to be determined: M^*, K_{rept} and K_{Rouse}.

3 Results and Discussion

The above theoretical model was implemented in gPROMS ModelBuilder software. The MWD of an LDPE grade obtained by simulation using a high-fidelity model developed previously [6], was used as input for the rheological model. The LCB content, also calculated by the high-fidelity model, was relatively low, which makes the proposed rheological model suitable. The plateau modulus G_N^0 was estimated using the literature value of Me = 1500 g/mol [8]. Parameter β was set at 2 as explained previously. The remaining parameters were fitted against experimental data of complex viscosity corresponding to a given LDPE grade, obtaining as a result $K_{rept} = 2E^{-9}$, $K_{rouse} = 2.28E^{-7}$ and $M^* = 70000$.

Figure 1 shows experimental data of the complex viscosity η^* as a function of ω, obtained at 180°C, 200°C and 220°C and subsequently unified at 190°C using the time-temperature superposition principle. It can be seen that the predicted curve is in good agreement with experimental data. Figure 2 displays the storage G' and loss G'' moduli.

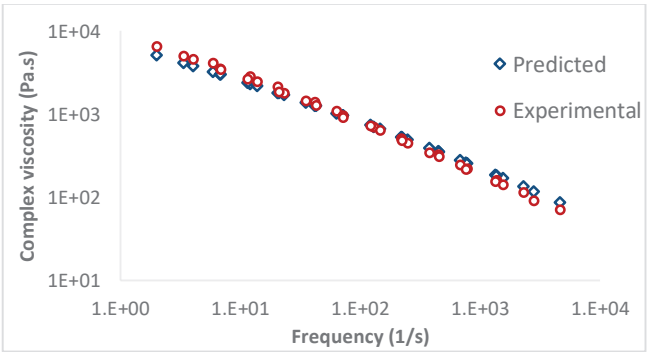

Fig. 1. Experimental and predicted complex viscosity curve of LDPE at 190°C.

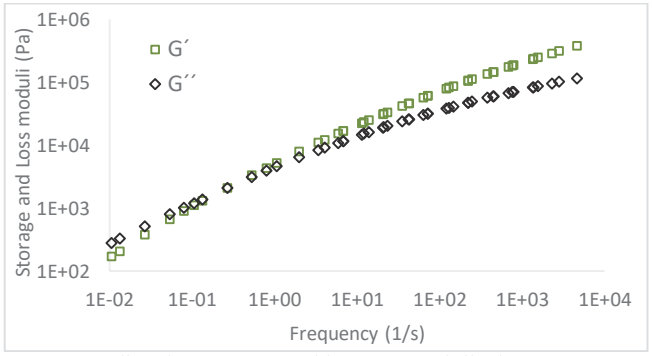

Fig. 2. Predicted storage G´ and loss G´´ moduli of LDPE.

4 Conclusion

A mathematical model for the prediction of rheological properties such as the relaxation modulus (G), dynamic moduli (G', G'') and the complex viscosity (η^*) of LDPE as a function of its MWD was applied. This model represents a useful tool to connect polymer production conditions with rheological end-use properties. For example, the complex viscosity curve could be subsequently used to predict end-use properties such as the polymer melt index, a quality control parameter very useful for polymer producers.

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Efficiency analysis and cavitation prediction: Choice of propeller most suitable for a Brazilian Navy ship

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Abstract. This paper aims to select the best propellant for the Patrol Ships (NPa) Grajaú class, making use of an Operational Research tool, the Holtrop-Mennen method. To enable this study, parameters and information obtained through consultations with equipment manuals, acquisition contracts and visits on board the NPa were used. After data collection, a comparative analysis was made between many types of conventional Series B propellers, varying several parameters, such as the number of blades, step/diameter and area ratios, in order to choose the one that, when integrated into the propulsion system, could meet the demands of the ship understudy, especially concerning the required thrust, efficiency and cavitation criterion. As a result, the two-blade propellant was considered more indicated to be used, notably because it presented the lowest occurrence of cavitation. This article represents great relevance for academia and society, because the methodology presented in this paper can be used in several situations, aiming at increasing efficiency and sustainability in naval propellants.

Keywords: Efficiency, Sustainability, Propellant, Cavitation, Operational Research.

1 Introduction

The "Grajaú" class patrol ships (NPa) were designed to have around 200 tons of displacement. They are employed in coastal patrol of Brazilian Jurisdictional Waters (AJB), towing maneuvers and refueling at sea. The class has 12 ships, built in English or Brazilian shipyards, having passed 15 years between the construction of the prototype and the last ship of the class. The first ship of the class was incorporated into the Brazilian Navy (MB) on December 1, 1993.

With the current situation of MB, which has been facing several budget cuts, it is necessary to operate the means efficiently, aiming at the use of available resources in

the best possible way, avoiding waste. Therefore, a well-designed and integrated propulsive system is of importance, as it is responsible for the generation of movement of the vessel and the consequent fulfillment of its mission.

In this context, Operational Research (OR) emerges as an excellent tool to solve the proposed problem - increasing efficiency. The term Operational Research appeared in 1939 during World War II but was little known and nothing studied [1]. The evolution of the OR happened even after the First Industrial Revolution, where the first problems began to arise. The tools provided by the OR offer the same solution that a decision-maker could reach through intuition and that such tools can be approached through deterministic models of mathematical programming [2].

The use of the OR is justified by the fact that it is a science composed of numerous techniques and models intrinsically related to the optimization of systems, and can be considered an optimization tool par excellence [3]. The brazilian academic production focused on military problems, especially naval ones, has not had much expressiveness, or dissemination, in the field of the OR and efficiency, to meet the potential of use in MB [4].

This paper aims to select a propellant that, integrated with the other components of the Propulsion System of the NPa Grajaú, provides the necessary thrust to the ship as efficiently as possible. Therefore, the main contribution of this study is presenting an efficiency analysis in a Brazilian Navy ship, which can be replicated to other civil and military vessels, contributing to raise the energy efficiency of the propulsive systems and consequently increase in environmental and economic sustainability.

2 Methodological Procedures

Initially, the components of the Propulsion System of NPa Grajaú were described, based on data contained in the equipment manuals, information collected from the acquisition contract and onboard the ships. It is noteworthy that, after data collection, the parameters not obtained, because they are confidential, were estimated.

Then, a comparative analysis was made between two, three and four-blade Series B-series propellers, varying their area ratios using KT-KQ-J diagrams. For this, the Holtrop-Mennen method [5] was used, which provides the total resistance to the feed and buoyancy required.

Finally, we analyzed cavitation criteria and evaluated the results obtained, with the consequent selection of the propellant considered the most suitable for the full fulfillment of the mission of the NPa Grajaú.

The first step in selecting a vessel's propulsion system is to estimate its forward strength. There are a few ways to obtain this estimate of advance resistance. In this work, the Holtrop-Mennen method was used. The method provides a prediction of the components of surface ships total resistance and is widely used at ships initial design stage for estimating the resistance [6].

2.1 Literature Review

The first step in selecting a vessel's propulsion system is to estimate its Effective Horse Power (EHP). There are a few ways to obtain this estimate of ship resistance. In this section, the important parameters for the proposed analysis will be described.

Ship Resistance (R_T). Consists of the sum of forces acting on the vessel when it sails at a given speed. Its estimation allows us to determine the power required for the displacement of the ship [7]. The most common solutions for calculating R_T are tank tests with scale models and the application of statistical methods. Academically it is common to use the statistical method Holtrop-Mennen, developed by [5].

Effective Horse Power (EHP). EHP comprises the power required to overcome the R_T to the movement for a given service speed (V_S). [8]. The equation for obtaining it is described in section 2.2.

Propeller. The most common type of propellant in naval propulsion systems is the helix, which is located at the stern of the vessel and has the function of converting torque into thrust, allowing the ship to overcome the ship resistance [9].

Diameter (D). The propeller diameter is equivalent to the diameter of the disc area. In theory, the larger the diameter, the greater the increase in efficiency, however, its specification depends on the space available at the stern of the vessel [10].

The cavitation phenomenon is also a preponderant aspect in the choice of diameter, because when there is the excessive velocity at the ends of the blade, there may be cavitation in it [11].

Pitch (P). The helix pitch is defined as the pitch of the blade section cut to 0.7 of the propeller radius. It is the displacement in the forward direction when the thruster performs a full turn. As well as the diameter, the pitch is selected according to the values available by the manufacturer. In most cases, there is a wide variety of options, which provides selection in favor of maximum efficiency [10].

Design Diagrams. The propeller performance is defined by testing with small-scale models. The results of the tests carried out in open water, that is, without the presence of the hull-propellant interface, compose a database represented in the form of performance diagrams [11]. Thus, some non-dimensional coefficients are calculated based on the helix parameters, which are: Torque coefficient (K_Q), Thrust coefficient (K_T) and the Advance number (J), which the mathematical formulations for obtaining these parameters will be addressed below.

The K_T and K_Q dimensional coefficients as a function of J, when analyzed graphically, conventionally provide an estimate of the propeller efficiency [12]. Fig. 1 shows a typical performance diagram of a propeller.

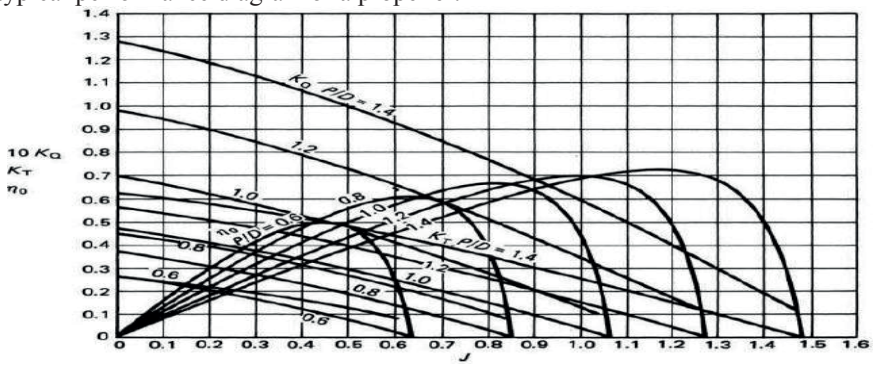

Fig. 1. KT-KQ-J diagram [11].

2.2 Hull-Propeller-Engine Integration

The presence of the hull induces disturbances to the flow around the propellant due to the separation of the flow and the formation of the trach. As a result, there is increased ship resistance and the difference between the average flow velocity around the propeller and the displacement speed of the vessel itself [13].

Thus, to estimate the thrust power and the ship speed necessary to anticipate these phenomena, certain coefficients deducted should be established by testing with similar vessels or by empirical and statistical methods. Such factors are known as the reduction of propellant power coefficient (t) and wake fraction coefficient (w).

Once these factors are determined, the thrust power (T) can be calculated by (1) [14]. R_T is obtained through the Holtrop-Mennen method, which will be introduced in chapter 3.

$$T = \frac{R_T}{1-t} \tag{1}$$

The advance speed propeller (V_a) is obtained through the relationship between the Service Speed (V_s) demanded by the V_s and w, according to (2).

$$Va = Vs(1-w) \tag{2}$$

The first parameter related to the hull-propeller interaction is defined from the hull efficiency (η_H), which consists of the ratio between the EHP and the Thrust Horse Power (THP), shown in (3)

$$\eta_H = \frac{EHP}{THP} = \frac{(R_T . V_S)}{(T.V_a)} \tag{3}$$

It is also possible to rewrite this equation through (4) [15].

$$\eta_H = \frac{(1-t)}{(1-w)} \tag{4}$$

Thus, it is possible to deduce the rotation propellant (n) as a function of (J, Va and D, defined according to (5) [15]:

$$n = \frac{Va}{J.D} \tag{5}$$

According to the resulting n value, it is possible to calculate the torque (Q) value that must be supplied to the propeller (6), as well as the Thrust (T) supplied by it (7) if operated in open water [16]. The K_Q coefficient value is graphically established from the performance curves of the propellant, considering the operation J.

$$Q = KQ.\rho.n_{hélice}^2.D^5 \tag{6}$$

$$T = KT.\rho.n_{hélice}^2.D^4 \tag{7}$$

However, the torque required by the propellant when it operates at the stern of the hull is different from the Q value, established for open water. The correction of this value refers to the Relative Rotating Efficiency (η_{RR}), specified in (8).

$$\eta_{RR} = \frac{Q_0}{Q_{hélice}} \tag{8}$$

2.3 Engine-Propeller Integration

The engine-propeller integration process aims to select the most suitable engine for the project so that it supplies torque to the propellant and has the best performance, i.e. the lowest fuel consumption [13]. For this selection, in possession of the required torque values (Q_{OPE}) and the propeller rotation of operation (n_{OPE}), the necessary power to be delivered to the propeller (W_{AP}) is determined, as indicated in (9) [15].

$$W_{AP} = 2\pi.Q_{OPE}.n_{OPE} \tag{9}$$

However, the power that the engine must provide to the propellant is given according to the transmission system efficiency, shown through (10)

$$W_{ENGINE} = \frac{W_{AP}}{\eta_T} \tag{10}$$

2.4 Cavitation criterion

When a propeller moves rapidly in water, the pressure in the adjacent liquid falls proportionally to the square of the local flow velocity. If local pressure falls below the vapor pressure of the surrounding liquid, small bubbles or vapor cavities are formed. Then, the flow decreases behind the object and these small cavities are collapsed with very high explosive force. If the cavitation area is large enough, it will alter the characteristics of the propeller, causing decreased thrust, torque change, damage to the propeller material (corrosion and erosion), strong excitation and vibration noises [12].

To obtain the cavitation criterion $\sigma_{0.7R}$, using the Relative speed V_R at 0.7 of the radius and the pressure on the propellant centerline (11):

$$\sigma_{0,7R} = \frac{p_0 - p_v + \rho g h}{\frac{1}{2}.\rho.(V_a{}^2 + (0,7\pi ND)^2)} \quad (11)$$

Considering the approximate values, it is possible to obtain (12):

$$\sigma_{0,7R} = \frac{188,2 + 19,62h}{V_a{}^2 + n^2 D^2} \quad (12)$$

Where h is the water column above the axis line (m), D is the propellant diameter (m) and n is the thruster rotation (RPS).

Also, the τc coefficient, which expresses the average thrust load on the propellant blades, must be calculated (13):

$$\tau_c = \frac{T/A_P}{\frac{1}{2}.\rho.(V_R)^2} \quad (13)$$

Where T is the thrust (KN), A_P is the projected blade area (m²) and V_R is given by $V_R{}^2 = V_a{}^2 + (0.7\pi nD)^2$. The projected area can be calculated by (14):

$$A_P \backsim A_D.\left(1,067 - 0,229.{}^{P}/_{D}\right) \quad (14)$$

2.5 NPa Grajaú Propulsion System Data

The propulsion system provided by MTU consists of a Main Combustion Engine (MCP) model MTU 16B 396 TB 94, with 16 cylinders in "V" and a maximum power of 2460 KW (2100 rpm). The reduction ratio is 3.074:1 through a gear coupling. The propellant is a B-series propeller with a diameter of 1.65m.

2.6 Holtrop-Mennen method

The method is a power prediction methodology based on a regression analysis of random model and full-scale test data. The method had been adjusted to test results obtained in some specific cases for many combinations of main dimensions and form coefficients.

The performance prediction models are typically used for the calculation of bare hull resistance, appendage resistance and propeller characteristic [17]. For conventional ships, the Holtrop-Mennen method is applicable to a wide variety of ship types. The method has been widely used to obtain resistance from the ship [18]–[20].

3 Comparative analysis of propellants

In this section will be made the comparative analysis of propellers with 2, 3, and 4 blades, area ratios of 1.05, 0.7, and 0.55 respectively, aiming to select the propellers that provide the necessary thrust for the ship to demand its service speed (12 knots) with the highest possible efficiency, besides being evaluated the occurrence of cavitation.

3.1 NPa Grajaú Propulsion System Data

To determine the ship resistance with greater precision, the values calculated through the Calculation Spreadsheet of the Holtrop-Mennen method were used. As their formulas are valid for typical forms of merchant ships, the results for other forms, such as a military ship, tend to be incoherent. For this reason, the ship was considered with only 1 propellant, parallel draught, and the coefficients of the waterline and master section were approximated to typical values of forms similar to NPa Grajaú (Fig. 2).

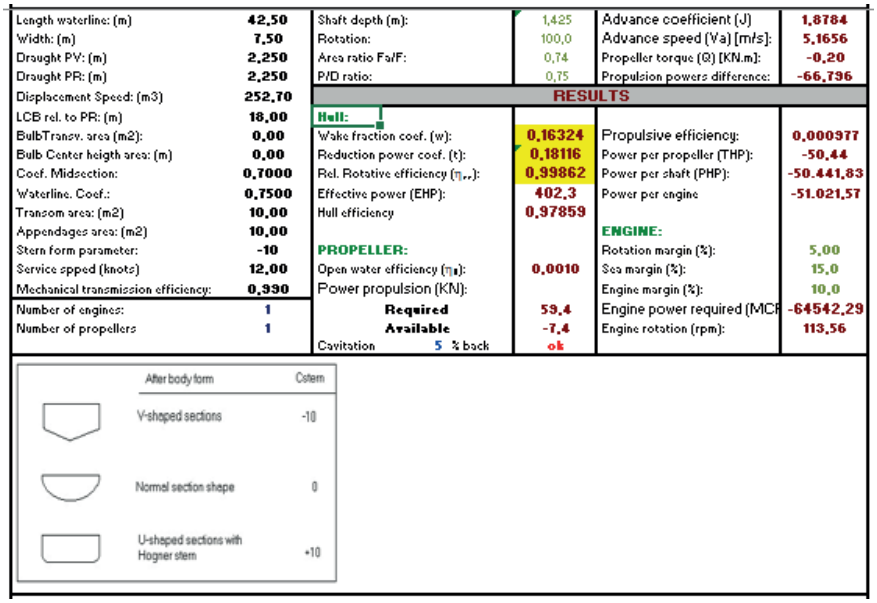

Fig.2. Holtrop-Mennen spreadsheet interface after entering the input data.

The results obtained by the method were: the SHIP resistance (RT) for the SPEED of 12 knots is 48.6 KN; t equal to 0.18829; w equal to 0.16816. Since t is known, it is possible to obtain the required T VALUE by (1). Thus, the result for T is 60 KN.

For the proposed analysis, we selected the propellers that provide the thrust necessary for the ship to demand its V_S (12 knots) as efficiently as possible. The propeller diameter will be considered 1.65m. For the two-blade propeller, all step-by-step calculations will be performed. The other blade configurations and area ratios will have their results presented in section 4.

3.2 Two-blade propeller with area ratio 1.05

To obtain the data related to this propellant, the design diagram for 2-blade propellers, area ratio of 1.05 and pitch/diameter ratio ranging from 0.5 to 1.4 was analyzed.

Table 1 summarizes the values found in the K_T-K_Q-J diagram. K_T and K_Q coefficients were used (6) and (7).

Table 1. Analysis of the K_T-K_Q-J diagram for the 2-blade propellant and area ratio 1.05.

T (KN)	K_T	*n (RPS)*	RPM	J	P/D	η_0 *(%)*
60	0,21937	6	360	0,50505	0,9	44
60	0,27083	5,4	324	0,56116	0,85	48
60	0,31590	5	300	0,60606	1,15	52
60	0,49359	4	240	0,75757	0,95	54

The highest efficiency was 54%, for the rotation of 240 RPM and P/D ratio 0.95.

Break Horse Power (BHP) calculation. Now the BHP power that must be supplied by the MCP will be calculated so that the propeller considered the most efficient can provide the thrust needed for the ship to reach the service speed.

First, EHP and THP are calculated using (15) and (16).

$$\mathrm{EHP} = \mathrm{R_T}.\mathrm{V_S} \tag{15}$$

$$\mathrm{THP} = \mathrm{T}.\mathrm{V_a} \tag{16}$$

After performing the calculations, EHP = 291.6 KW and THP = 300 KW. With the value of THP, it is possible to find DHP, by using (17).

$$\mathrm{DHP} = \frac{\mathrm{THP}}{\eta_0} \tag{17}$$

The value of DHP = 517.24 KW is found. From this point on, the sea (20%), operational (10%) and engine rotation (10%) margins will be introduced. To facilitate calculations, the powers will be used, as below:

To facilitate calculations, the powers will be used, as below:

BHP_1 = DHP

BHP_2 = BHP_1 after the seashore is applied.

BHP_3 = BHP_2 after the operating margin of the engine is applied.

BHP_4 = BHP_3 after the engine speed margin is applied.

When the 20% sea margin is applied in DHP, BHP_2 equal to 620.7 KW is obtained. With the value of BHP_2, it is possible to obtain the value of RPM_2, through (18).

$$\frac{BHP_2}{BHP_1} = \left(\frac{RPM_2}{RPM_1}\right)^3 \tag{18}$$

So RPM_2 = 255 RPM. When the operating margin is applied, BHP_3 is equal to 682.8 KW. Using (18), the value of RPM_3 = 263.3 RPM is found.

Applying the rotation margin, the RPM_4 value is equal to 289.6 KW. Finally, it is found the value of BHP_4 equal to 908.8 KW, power that must be supplied by the MCP so that the propeller under analysis can provide the thrust required for the ship to demand the service speed of 12 knots. Using (18) once again, the engine RPM is equal to 890 RPM.

3.3 Three-Blade Propeller with Area Ratio 0.7

To obtain the data related to this propellant, the diagram for three-blade propellers, an area ratio of 0.7 and pitch/diameter ratio ranging from 0.5 to 1.4 was analyzed. The highest efficiency is 54%, for a P/D ratio of 0.8.

3.4 Four-Blade Propeller with Area Ratio 0.55

To obtain the data related to this propellant, the diagram for four-blade propellers, area ratio of 0.55 and pitch/diameter ratio ranging from 0.5 to 1.4 was analyzed. The highest efficiency is 53% and P/D ratio of 0.75.

3.5 Analysis of cavitation occurrence in the propellers

Considering that the occurrence of cavitation in military ship thrusters is quite harmful, the Burril diagram will be used to evaluate cavitation in the thrusters considered the most efficient for each configuration of the number of blades and ratio of areas.
For this analysis, the two input parameters in the Burril diagram should be found, using (11), (12), (13) and (14). Figure 3 and Table 2 present the results for the three propellers considered the most efficient operating at the service speed.

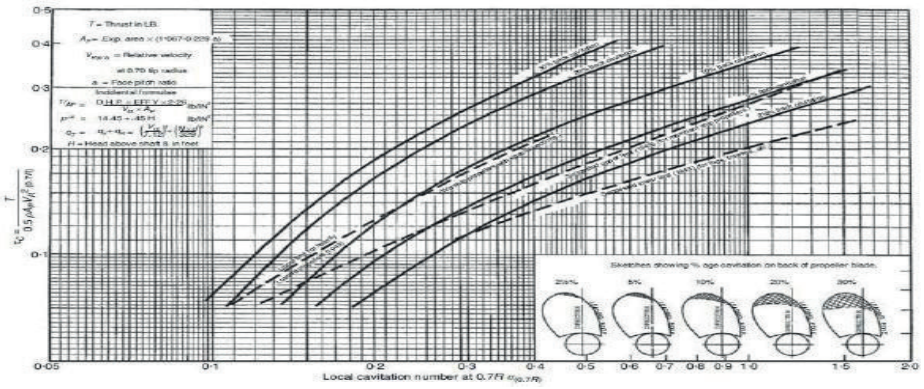

Fig.3. Burril diagram.

Table 2. Analysis of cavitation criteria for the most efficient propellers.

Propel-lant	Va (m/s)	P/A	AE /A0	T (N)	N (RPS)	RPM (propeller)	σ (0.7R)	τ_c	Cavita-tion
2 blades	5	0,95	1,05	60000	4	240	0,9	0,26	Below 2.5%
3 blades	5	0,8	0,7	60000	4	240	0,9	0,37	Above 10%

4 blades	5	0,75	0,55	60000	4	240	0,9	0,47	Above 10%

4 Analysis of Results

Evaluating the results for each propellant analyzed separately, it was possible to observe that, as the rotation decreases, the efficiency in open water increased. This occurred for all propellers, regardless of the number of blades and area ratios.

Table 3 summarizes the data of the propellants considered the most efficient for each configuration of the number of blades and area ratios previously evaluated.

Table 3. Most efficient propellants for each configuration of number of blades and area ratios.

Propellant	V_S (Knots)	P/A	A/A_0	T (N)	n (RPS)	RPM (propeller)	K_T	J	η_0 (%)
2 blades	12	0,95	1,05	60000	4	240	0,219	0,505	54
3 blades	12	0,8	0,7	60000	4	240	0,270	0,561	54
4 blades	12	0,75	0,55	60000	4	240	0,315	0,606	53

It was verified that all the maximum efficiencies found were very close because the increase in efficiency resulting from the decrease in the number of blades was counterbalanced by the decrease in the area ratios, which would tend to cause the performance of the thrusters to decrease.

It is concluded that it is not possible to state which propellant is most suitable for the NPa Grajaú if only the performance of each propeller is taken into account. Analyzing now the integration of the propellers with the MCP, table 4 is reached.

Table 4. Integration of each propeller with the MCP, operating at the service speed.

Propellant	T (N)	η_0 (%)	N (RPS)	RPM propeller	EHP	THP	DHP	BHP	RPM engine
2 blades	60000	54	4	240	291.600	3.000.000	555,5	976,1	890,2236
3 blades	60000	54	4	240	291.600	3.000.000	555,5	976,1	890,2236
4 blades	60000	53	4	240	291.600	3.000.000	566,1	994,5	890,2236

It is possible to observe that all propellants require the same MCP rotation to provide the thrust necessary for the ship to demand the service speed. It is verified that the MCP of the ship is fully able to provide the thrust required for all the propellers analyzed.

Analyzing the cavitation criteria, shown in the table 2, it is verified that the two-blade propellant has the lowest cavitation level. After the three proposed analyses, considering the efficiencies and the parameters of hull-propeller-engine integration were very similar for all the propellants analyzed, the two-blade propellant was considered the most suitable for the NPa Grajaú, as it has the lowest cavitation index among all of them.

Given the above, the propellant selected for the NPa Grajaú was the two-blade propeller, area ratio 1.05 and P/D ratio equal to 0.95.

5 Conclusion

The objectives of this paper were achieved, considering that, after all the analyses and calculations performed, it was possible to select a propellant that met all the requirements stipulated for the ship, concerning the required thrust, integration with the MCP and cavitation criteria.

The methodology presented in this paper can be used in several naval propulsion systems, aiming to increase propulsive efficiency, contributing greatly to the economy of resources and the preservation of the environment.

One factor that offered some limitation to the analysis proposed in this work was the use of the Holtrop-Mennen method, which is not indicated for unconventional forms, as is the case of military ships. However, since most of the parameters of these ships are confidential, there was no other alternative for performing the calculations. Even with this limitation, the results obtained with the estimates were satisfactory.

In cases such as this work, in which the shape of the ship under study is outside the scope of the Holtrop-Mennen method, some other methods, such as CFD (Computational Fluids Dynamics), which uses finite element method for calculations, solving equations that represent the behavior of the flow of a fluid in a domain with certain boundary conditions [21]. Another way to improve the analysis would be to obtain the hydrostatic tables of the ship.

Future researches could address analyses of ship's propulsive systems with ostentatious parameters, which would bring the results very close to reality. Another suggestion would be to design the propulsive system as a whole, which would make the analysis much more interesting and complex.

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Comparative analysis between waterjet and conventional propulsion: A new possibility for use in Brazilian Navy Ships

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Abstract. This paper aims to verify the feasibility of using waterjet propulsion in Brazilian Navy (MB) ships, in view of the limitation that conventional propulsion presents mainly in regions of low depth and difficult maneuverability, such as riverside and wetlands. For this, Operational Research (OR) was used, through the Holtrop-Mennen method, to compare the efficiencies of waterjet and conventional propulsion, operating in three velocity ranges: 12, 21 and 35 knots. In addition, the main energy and operational characteristics of the waterjet propulsion system were studied, highlighting its advantages and disadvantages and some cases of waterjet application in military ships were exemplified, evaluating the feasibility of implementing this type of propulsion in other MB ships. The results show that waterjet is more efficient than conventional propulsion for vessels that spend high speeds, especially in riverside and Pantanal operations, and this characteristic can be very useful to MB, contributing to the increase of inspection capacity in the Brazilian Jurisdictional Waters (AJB). Therefore, this article represents great relevance for academia and society, as it presents a methodology that allows verifying which type of propulsion is most efficient, which can be used by civil and military naval sectors, aiming to choose the most appropriate type of propulsion to achieve its objectives.

Keywords: Efficiency analysis, Waterjet propulsion, Military application.

1 Introduction

The Brazilian Navy (MB) has as the main mission the guarantee of national sovereignty in Brazilian Jurisdictional Waters (AJB). For this, the means employed must be modern, versatile, robust and efficient. It was identified a difficulty in fulfilling this mission,

especially in riverside and wetlands, where the small depths and the presence of logs and debris in the water represent risks to the integrity of traditional outboard engines, which limits surveillance in these regions.

Such limitations in the supervision by MB naturally tend to increase the number of illegal actions in these areas, especially with regard to smuggling, illicit fishing and drug trafficking. Thus, the implementation of propulsion systems that will resolve these limitations would be a very useful way to improve the operating conditions of surveillance vessels in these sensitive regions, which would greatly increase the ability to fulfill their missions.

Nowadays, some more advanced types of propulsion, such as waterjet, gain enormous relevance because they offer advantages in terms of versatility and speed spent in regions of difficult maneuverability. In addition to the operational aspects, the efficiency in fuel consumption is of great importance, given the difficult situation in which the Brazilian economy is located and, consequently, MB, which has been facing several budget cuts in recent years.

Taking into account that conventional propulsion has proven not to offer good efficiency at high speeds [1], it is necessary to carry out feasibility studies for the implementation of alternative propulsion types, which offer better performance concerning fuel consumption in this operating condition.

Given the above, this paper aims to verify the feasibility of installing waterjet propulsion in MB's small, medium and large vessels, evaluating the advantages and disadvantages of this system when compared to conventional propulsion.

The article is divided in 5 parts. In section 2, the description of waterjet propulsion is made, addressing physical and thermodynamic principles. Then, in section 3, the main operational and technical characteristics of the use of waterjet propulsion are studied. Besides, it will be presented its use in ships of foreign Navies and also in small vessels of MB and some relevant data regarding the construction project of the National Corvette. In section 4, the methodology is described and a comparative analysis between conventional propulsion and waterjet propulsion is performed, highlighting the aspects concerning efficiency under different operating conditions and advantages of one in relation to the other. Finally, in section 5, the article is concluded.

2 Background

In this section the waterjet propulsion system is described, as well as its physical and thermodynamic aspects are detailed.

2.1 Literature Review

The waterjet is a marine propulsion device in which water is supplied to an internal pump that adds energy to the fluid and expels it from the stern of the vessel at high speed [2]. The concept of waterjet propulsion dates back to 1661 when Toogood and Hays first proposed this form of propulsion. Its use in the intervening years has been confined mainly to small high-speed pleasure craft and working boat situations where high maneuverability is necessary [3].

It is observed that the waterjet started to be used in medium and even large vessels, which was possible due to the considerable increase in the propelling unit sizes by waterjet. The reason for the comparatively smaller use of the waterjet compared to the conventional propeller is that this was generally considered simpler, lighter and more efficient. However, the introduction of more efficient pumps, in addition to the need for higher speed vessels are the main reasons for the rapid growth of the waterjet [3].

2.2 Description of the waterjet propulsion system

A waterjet installation mounted on the stern can be divided into four components: the inlet, pump, nozzle and steering device. The main component is the pump, which produces the jet at the nozzle outlet. In general, the stator basin and nozzle are integrated into one piece. The combination of the pump unit and nozzle is considered as waterjet pump. The system of ducts connected to the pump is called input [4]. The waterjet illustrated in Fig. 1 shows a built-in inlet duct, used, for example, on fast ferries and high-speed motor yachts.

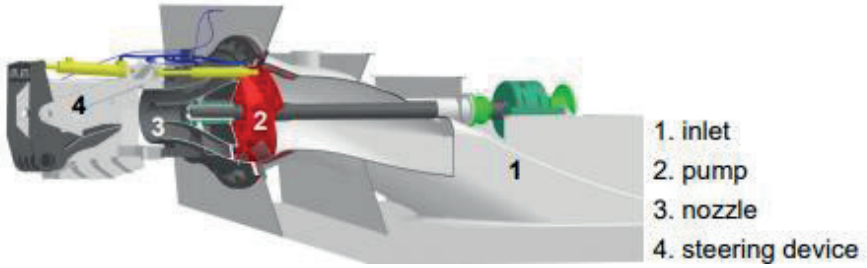

Fig. 1. Three-dimensional view of a waterjet installation [4].

In addition to the inline input, the inputs of type "ram" and "scoop" are mentioned, which have an opening that is more or less perpendicular to the direction of the flow, while the entrance opening mounted on the wall is parallel to the flow. Above the nozzle, there is a steering device, which can divert the jet of water in order to create steering and reversing forces. There are also facilities for deflection of the jet, constituting the option of reversal, useful for operating with machines in reverse or even for quick stop maneuvers [5].

The principle of operation of the waterjet is similar to that of jet aircraft turbines. The water from the underside of the vessel is aspirated, pressurized and thrown back at high speed. This forces the boat to move forward, creating movement. Its functioning is based on Newton's third law: "The whole force of action corresponds to a reaction force of the same intensity and contrary direction". The steering system works by directing the water jet sideways. Similarly, it can activate the reverser to get machines in reverse. It is a propulsion system that eliminates reversors, long shafts, propellers and rudders.

2.3 Physical and thermodynamic principles of waterjet

As a basis for considering the principles of waterjet propulsion, fig. 2 can be taken as a reference, showing an idealized waterjet system.

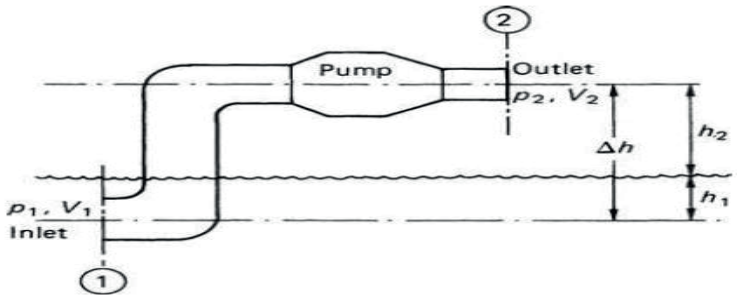

Fig. 2. Idealized waterjet system [3].

Based on this diagram, it is assumed that the water enters the system with velocity V_1 and leaves with a different velocity V_2 through a nozzle of area A_2. The water mass flow by the water jet is then given by (1) [6]:

$$\dot{m} = \rho A_2 V_2 \tag{1}$$

Where ρ is the density of water. Thus, the increase in the rate of moment change of water passing through the waterjet is given by (2):

$$\mathbf{\rho A_2 V_2 (V_2 - V_1)} \tag{2}$$

Because the force is equal to the rate of moment change, the thrust (T) produced by the system is given by (3):

$$\mathbf{T = \rho A_2 V_2 (V_2 - V_1)} \tag{3}$$

And the propulsion power (P_T) is given by (4):

$$\mathbf{P_T = TV_S = \dot{m} V_S (V_2 - V_1)} \tag{4}$$

Where V_S is the speed of the ship. Now, to derive a useful expression for the power required to drive the waterjet system it is necessary to resort to the general energy equation of the mechanical fluid and to apply this between the input and output of the unit (5):

$$\mathbf{\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + H_p = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + \Delta h + h_{loss}} \tag{5}$$

Where H_p is the portion associated with the potential energy supplied to the system by the waterjet pump; $\mathbf{\Delta}_h$ is the load loss between the inlet and outlet of the waterjet

(i.e. = h_1 - h_2); h_{loss} is the portion associated with the load losses of the flow by the system and also the load loss in the pump.

In the case of the difference between the inlet and outlet of the waterjet system, it should be noted that this will be a variable between the initial conditions and navigation conditions. The term of loss, h_{perda}, is associated with frictional losses that occur during the flow passage through the curves of the ducts and the various system obstructions that can prevent the flow during its passage through the unit.

For practical purposes, we can assume that p_2 is constant above the waterline, given that the altitudes involved and their effect on ambient pressure are small. With this, equation 5 can be rewritten as (6):

$$\mathbf{H_P} = \frac{\mathbf{V_2^2 - V_1^2}}{\mathbf{2g}} + \mathbf{h_2} + \mathbf{h}_{loss} \tag{6}$$

Now the energy transferred to the water by the pump can be expressed in terms of energy per unit of time as $\dot{m}\mathbf{gH_P}$, which, from (6) leads to (7):

$$\mathrm{P_{pump}} = \dot{m}\left[\frac{1}{2}(\mathrm{V_2^2} - \mathrm{V_1^2}) + \mathrm{g(h_2 + h_{loss})}\right] \tag{7}$$

Thus, it is possible to calculate the efficiency in open water equivalent of the waterjet, which can be defined from (4) and (7), being the ratio between the thrust power and the delivered power, as follows (8):

$$\boldsymbol{\eta_0} = \frac{\mathbf{V_S(V_2 - V_1)}}{\left[\frac{1}{2}(\mathbf{V_2^2 - V_1^2}) + \mathbf{g(h_2 + h_{loss})}\right]} \tag{8}$$

By analogy with the propellers, the efficiency of the waterjet pump can be expressed as (9) [7]:

$$\boldsymbol{\eta_{pump}} = \frac{\boldsymbol{\Phi\psi}}{\mathbf{2\pi K_Q}} \tag{9}$$

Where φ and $\boldsymbol{\psi}$ are the flow and energy transfer coefficients, defined respectively by (10) (11):

$$\boldsymbol{\Phi} = \frac{\mathbf{Q}}{\mathbf{ND^3}} \tag{10}$$

$$\boldsymbol{\psi} = \frac{\mathbf{gH}}{\mathbf{N^2D^2}} \tag{11}$$

Where K_Q is the normal torque coefficient of the conventional propeller.

Given that the pump value is higher for a jet of water than a propeller, this is not the basis on which the comparison should be made. An appropriate comparison can only be made in terms of the quasi-propellant coefficient, which for the propeller, includes the hull and relative rotating efficiency. For the waterjet, (8) should be observed, as well an appropriate hull coefficient covering the effect of the waterjet.

One good solution is using a parametric model for the description of the behavior of the waterjet-hull set, which allows the separate identification of the interaction between

the terms that interfere in the mutual relationship between the waterjet and the hull of the ship [8].

3 Operational and technical features of waterjet propulsion

The principle of waterjet provides high maneuverability to the vessel, because it is a propulsion system with full steering capacity. Most waterjet units are equipped with steerable nozzles or deflectors, which provide directional jet control. The steering capacity in each of these cases is produced by the reaction to the momentum change of the jet [3], as can be seen in Fig. 3:

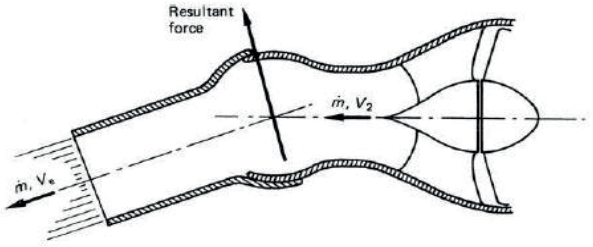

Fig. 3. Principle of waterjet maneuverability [3].

The angle at which the jet can be directed is variable, depending on the particular design of each manufacturer; however, it is generally expected to be of the order of ± 30°.

Concerning the capabilities of stopping, slowing, or reversing the flow of the water jet, these changes are usually achieved with the aid of a reverser, with the stopping force being produced by changing momentum principles. The design of the reversing device can be in a simple way, or it can be in a more sophisticated way, which allows a "shedding" of the jet to give good control to the braking forces, as shown in Fig. 4:



Fig. 4. Mechanism of waterjet thrust control [9].

With this latter type of system, the resulting thrust can also be continuously varied, from zero to maximum, in any power configuration for the engine. The latest technological advances in waterjets have put them ahead of conventional propeller systems for many types of high-speed marine applications, including military ships, ferries and pleasure craft. Modern waterjets offer several advantages, such as high efficiency, fast acceleration and excellent maneuverability [10].

In addition to operational advantages, submerged waterjets offer weight and space savings in the propulsion system and can be considered a key factor for propulsion on smaller platforms [11]. The benefits in terms of general layout and machinery arrangement could allow alternative uses of space to be considered, for example, the implementation of portable systems on board, or even for launch and collection stations. The advantages of the waterjet, when compared to the conventional outboard engine, will be analyzed in detail below.

3.1 Security

In contrast to the conventional outboard engine, waterjet propulsion is not threatened by floating solid fragments such as logs, ropes or fishing nets. Swimmers and divers are not at risk of suction by the propellant, which can occur with conventional outboard engines. This advantage is of great use to the military ships, which constantly operate with divers and researchers, and are often forced to stop machines because they operate with conventional outboard engines.

3.2 Maneuverability

Maneuverability is one of the most important characteristics of ships. In this context, the waterjet is very relevant because, even at a low speed, it provides excellent maneuverability due to the high versatility of the spatial position of the output nozzle, which provides modular thrust power and variable direction to the ship [12]. This is very useful for military ships, as it allows 360° spin maneuvers on the axis itself, as well as front and reverses maneuvers without strides and the need for full deceleration.

3.3 Efficiency

Fig. 5 shows the estimated efficiency of several types of propulsion systems in function of ship speed.

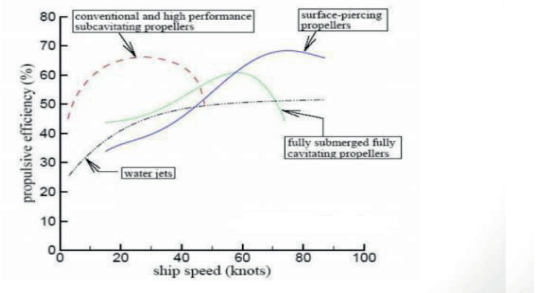

Fig. 5. Efficiency of propellers in relation to ship speed [1].

Analyzing fig. 5, it is observed that, for speeds of up to 45 knots, conventional propellers have higher efficiency than waterjet. However, it is verified that for speeds greater than 22 knots, conventional propellers show a efficiency drop, reaching their maximum speed at about 45 knots. From this point on, the use of other types of propulsion, such as surface and supercavitating propellers, is justified.

Note: 1 knot means one mile/h, approximately 1.852 m/h.

Supercavitating propellers have their highest efficiency at speeds of approximately 60 knots. From this point on, the use of surface propellers is justified, which present greater efficiency at speeds of about 80 knots.

Analyzing the waterjet, it is noted that its efficiency remains practically constant at speeds from 40 to almost 90 knots. Although supercavitating and surface propellers are more efficient than waterjet, they do not offer protection to propellers, which is essential for operation in low-depth regions. Therefore, analyzing the waterjets in relation to the conventional propulsion of subcavitating propellers, it is noted that, without taking into account the protection advantage of the propellant, waterjet propulsion is more efficient at speeds above 45 knots.

3.4 Noise and Cavitation

Compared to the conventional outboard, the waterjet ensures lower noise and vibration levels [13]. This factor is extremely important for military vessels because the less noise is emitted, the more they can omit their acoustic signature and, consequently, hinder detection by enemy sensors.

3.5 Grounding

Grounding maneuver is very common in river navigation, whether intentional or accidental. Waterjet propulsion offers the ability for the ship to land or even disengage only with the use of the propellant, as it provides high thrust power. This characteristic is very favorable to military ships, as it allows access to inhospitable and winding regions without endangering the integrity of the ship and propellant.

3.6 Use of waterjet in foreign Navies

Waterjet is increasingly being applied to military ships from developed countries such as the United States, South Korea, Finland and Norway. Waterjet propulsion offers significant advantages in many high-speed or special purpose ships, such as military ships [14].

As examples of waterjet applications in military ships it is possible to cite Littoral Combatant Ship (LCS) program of the U.S. Navy. They are the largest ships ever built that employ waterjet - the USS Freedom (LCS- 1) and USS Independence (LCS-2) -, which have a total length of respectively 115 and 127 meters.

In addition to the use in medium and large ships, the application of waterjet propulsion in amphibious assault vehicles and submarines of foreign navies stands out.

3.7 Use of Waterjet in MB

This section discusses the use of waterjet in MB small crafts, which are among the newest and most modern in the Brazilian fleet.

Pacific 24 speedboat. The PACIFIC 24 is a semi-rigid hull speedboat with the waterjet propulsion system, manufactured by VT Halmatic. Its main functions are rescue, visit inspection/approach actions, and can be used secondarily for transporting material and personnel.

DGS 888 Raptor. The DGS 888 Raptor is an armored multimission vessel designed to operate in harsh environments. It features the powerful FPT Industrial N67 EVO engine, which delivers 570 HP to an AlamarinJet AJ340 waterjet propulsion system, and enables the vessel to reach speeds of more than 42 knots, and has noise and vibration reduction.

Brazilian Corvette Project. The use of waterjets compensates in terms of efficiency and consequently in financial terms from the operation of the medium at speeds predominantly above 25 knots [15]. Fig. 7 illustrates efficiency in function of the ship speed in general. This occurs because, at high speeds, the water flow over the intake duct increases, reducing the work needed to be attended by the impelling ones.



Fig. 6. Efficiency of conventional and waterjets propellants [16].

In order to verify the possibility of obtaining more economically viable propulsion for the new Brazilian Corvettes at lower speeds, a study about mixed propulsive arrangements, using propellers and waterjets, was conducted [17]. Thus, it would be used the conventional propellers for lower speeds and waterjets for higher speeds. After the tests, it was concluded that two MTU 16V 1163 M94 engines (one per shaft) would provide power to the propellers. To meet the power required by the waterjets, the GE LM2500+G4 turbine would be selected [17].

4 Methodology

An appropriate comparison between waterjet and conventional propeller can only be made in terms of the quasi-propulsive coefficient [3]. Given the above, in this chapter, a comparative analysis will be made between the quasi-propulsive efficiencies of the waterjet and a conventional propellant to provide the same thrust to the ship.

To enable the proposed analysis, the Holtrop-Mennen method [18] was used to obtain the quasi-propulsive efficiency of the conventional propellant. The method consists of a series of mathematical formulations that were obtained through the use of regressions based on random models and real-scale data in the Netherlands Ship Model Basin [19].

4.1 Comparative analysis between waterjet and conventional propulsion systems

To obtain the parameters of the conventional propulsion to be compared, the Holtrop-Mennen method [18] was applied to the data of the propulsion system of the Patrol Ship (NPa) Grajaú. As its formulas are valid for typical forms of merchant ships, the results for other forms, such as a military ship, tend to be incoherent. For this reason, the ship was considered with only 1 propellant, parallel draught, and the coefficients of the waterline and master section were approximated to typical values of forms similar to NPa Grajaú (Fig. 7).

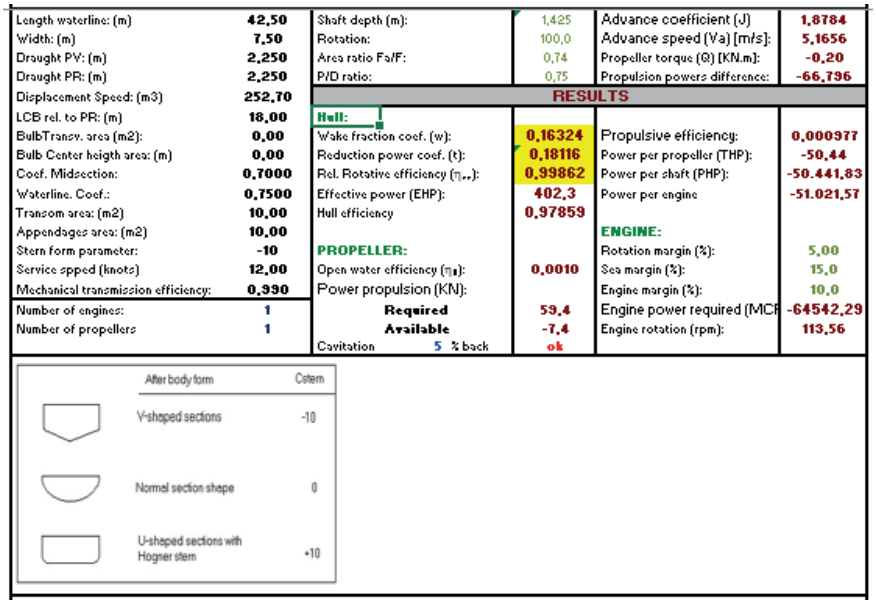

Fig.7. Holtrop-Mennen spreadsheet interface after entering the input data.

For the proposed analysis, we selected the propellers that provide the thrust necessary for the ship to demand three ranges of Ship Speed (VS) - 12, 21 and 35 knots - as efficiently as possible. The propellant considered the most efficient after the method application has 2 blades, diameter of 1.65 m, area ratio equal to 1.05 and the following features (Table 1):

Table 1. Operating parameters of the propellant operating at the three speeds analyzed.

V_s (knots)	V_a (m/s)	T (KN)	K_T	n (RPS)	RPM	J	P/D	η_0
12	5	60	0,493	4	240	0,7575	0,95	54
21	9	182,3	0,462	7,2	432	0,7575	0,95	49
35	15	262,6	0,345	10	600	0,9163	0,95	44

The conventional propellant and the waterjet operating in three-speed ranges will be compared: 12, 21 and 35 knots. Ressalta-

For the calculations related to the waterjet, the following premises will be established:

1. The vertical and horizontal inclination angle of the waterjet will be considered equal to zero;
2. "Vena contracta" occurs in the output plane of the nozzle (A_j=A_n); The advance speed (V_a) is uniform;
3. Pump losses are included in stator losses;
4. The wake fraction coefficient (w) and reduction of propulsive power (t) were obtained by Holtrop-Mennen method and considered equal for both propellers;
5. The pressure coefficient was considered equal to 0.07, and h_j was considered equal to 0.06584, based on previous studies [16];
6. The jet area A_j was considered equal to 2.7449 m^2, obtained for a waterjet operating to provide a thrust power required for the NPa Grajaú to demand the service speed (12 knots) (12) (13) (14).

$$\eta_D = \eta_H \cdot \eta_0 \cdot \eta_{rr} \tag{12}$$

$$\mu = (1 - w)\frac{V_s}{V_j} \tag{13}$$

$$\eta_D = \frac{\eta_P \cdot \eta_r \cdot \left(\frac{1-t}{1-w}\right) \cdot 2\mu(1-\mu)}{1+\psi-(1-\zeta)\mu^2+\frac{2gh_j}{V_j^2}-\frac{C_P \cdot \mu^2}{(1-w)^2}} \tag{14}$$

After applying the calculations, the quasi-propulsive efficiency for the conventional propeller and the waterjet is obtained, according to Table 2:

Table 2. Comparative analysis between hydrojet and conventional propulsion.

V_s (knots)	Conventional Propulsion		Waterjet	
12	η_0	0,54	$\eta_{jet}*\eta_{pump}$	0,44
	η_{rr}	0,99	η_{rr}	1
	η_H	0,9761	η_H	0,97
	η_d	0,521	η_d	0,43
21	η_0	0,49	$\eta_{jet}*\eta_{pump}$	0,48
	η_{rr}	0,99	η_{rr}	1
	η_H	0,97	η_H	0,97
	η_d	0,47	η_d	0,48
35	η_0	0,44	$\eta_{jet}*\eta_{pump}$	0,53
	η_{rr}	0,99	η_{rr}	1
	η_H	0,97	η_H	0,97
	η_d	0,43	η_d	0,52

Evaluating the results of table 2, it is concluded that:

1. For the speed of 12 knots, the conventional propellant presented higher efficiency than the waterjet; at the speed of 21 knots, the two thrusters presented very close efficiencies, with a slight advantage for the conventional (about 1%); at the speed of 35 knots, the waterjet proved to be much more efficient than the conventional one.

2. In short, waterjet propulsion is justified for ships that need to develop speeds greater than 25 knots (as shown in Fig. 7), such as warships and small vessels operating in the Amazon. Besides, after the study carried out in section 3, it remains clear that the maneuverability and safety provided by the waterjet in relation to conventional propulsion present significative advantages for vessels operating in areas with low depth and presenting obstacles, such as riverside regions.

3. In the case of vessels that need to develop speeds below the threshold of 25 knots, if the criterion evaluated is only energy efficiency, it is observed that conventional propulsion is more advantageous.

5 Conclusion

In view of the above findings, the waterjet propulsion system can be very useful for MB vessels, mainly for operation in regions with small depths, with floating solid fragments, such as trunks, ropes or fishing nets and winding terrain, such as the wetland and rivers of the Northern region of the country. The high maneuverability and speed provided by the waterjet would be very useful for the fulfillment of MB's mission in these areas.

In the comparative analysis between waterjet and conventional propeller, it was clear that the speed of the ship is a primary factor to evaluate which type of propellant is most

efficient. Therefore, before choosing the most suitable propellant, it is necessary to determine the speed of operation of the ship. The installation of waterjet is justified in vessels that spend high speeds (above 25 knots), mainly small boats, such as organic boats of larger ships.

Regarding to the construction project of the national corvette, it was possible to observe that MB envisions the implementation of the waterjet propulsion system also in large ships, being used mainly in hybrid arrangements, taking advantage of the fact that each propellant presents a certain range of greater efficiency, and that these features complement each other.

The use of waterjet propulsion systems is a very broad issue, given the wide range of vessels that can use it. In this paper, only the military uses of waterjet were addressed, and it was verified that this propellant is increasingly used for this scope, as it offers very important operational and functional advantages for this purpose.

One factor that offered some limitation to the analysis proposed in this paper was the use of the Holtrop-Mennen method, which is not indicated for unconventional forms, as is the case of military ships. However, since most of the parameters of these ships are confidential, there was no other alternative for performing the calculations. Even with this limitation, the results obtained with the estimates were satisfactory.

Future works could study the use of software such as CFD to determine the pressure and the thrust power, given that these parameters are extremely important for waterjet efficiency.

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System dynamics for flood impact assessment. Case study of two municipalities in South America

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Abstract. Each year, in South America, flooding related disasters cause millions of dollars' worth in damage and hundreds of casualties. In this context, humanitarian logistics provide tools to improve the preparedness of vulnerable communities. In this paper, an approach based on system dynamics modeling is proposed to evaluate the expected short- and medium-term impacts and expected recovery time in two municipalities located in South America, characterized by flooding risk, especially during the April - June season when the augmentation of the average precipitation levels occurs. The real cases of Chia (Colombia) and Santa Ana del Yacuma (Bolivia) are analyzed and compared.

Keywords: System Dynamics, Floods, Humanitarian relief operations, risk management.

1 Introduction

In the last decade, humanitarian operations have gained great importance due to the high levels of uncertainty and elevated monetary costs which are to be found within a humanitarian relief context (Tomasini & Wassenhove, 2009). Considering the impact humanitarian crisis can cause, contributions to evaluate and mitigate its effect has gained significant attention. These include the study of medical goods distribution or transportation of injured population, inventory management problems, location, and management of physical resources such as food, clothing or raw materials, and the supply chain design of humanitarian systems characterized by the necessity for quick and efficient response.

In South America, according to recorded data, in the last 30 years, natural disasters have affected near 103.8 Million people and have caused at least 60 thousand deaths (Centre for Research on the Epidemiology of Disasters, 2019). Since 1990, the most frequent natural disasters registered in South America are flood events. Thus, floods are considered as a constant threat for populations located near water sources, such as

rivers, ravines, creeks, lakes, etc. Given the likelihood of flooding during months with high levels of rain precipitation, governments throughout South America, have employed a vast amount of resources for the prevention, mitigation, and response.

Humanitarian and relief operations in flooding events are characterized by an increasing need for quick and efficient response. In the last decade, researchers have developed several methods for dealing with humanitarian problems based on optimization techniques, such as linear and stochastic programming; however, as far as we know, there is a lack of research incorporating System Dynamics (SD) as a tool for risk assessment, damage mitigation and humanitarian logistics operations planning for dealing with flooding events (Haiyan et al., 2020).

In this paper, an approach based on SD modeling is proposed to evaluate the expected short- and medium-term impacts and expected recovery time in two municipalities located in South America, i.e., Santa Ana del Yacuma, Bolivia and Chía, Colombia, characterized by flooding risk due to their proximity to rivers, especially during the April - June season when the augmentation of the average precipitation levels occurs.

SD is chosen as a modelling approach since it provides advantages to understand behaviors of quantitative and qualitative variables within complex systems over significant time horizons (Sterman, 2000).

2 Risk Assessment Model

The proposed SD model is composed by three sub systems, defined as (SS#). The model aims to reflect the resulting behavior of the studied populations after a flooding event happens limiting the inflow of food to the municipalities.

The first subsystem **(SS1)** represents the state of the access roads for each one of the municipalities measured in the fraction of enabled or disabled roads. This sub-system considers the possible impact caused by flooding events and the government's reaction speed after the disaster, the expected reaction time, and the fluctuating need for higher or lower repairing rates for the roads. In this sub-system a flood-related disaster is bound to occur in a specific time**,** allowing the simulation to reach a stable state regarding the population's behavior before and after the flooding event happens.

SS2 aims to measure the impact of the edible goods that arrive to the population. This sub-system represents and measures the amount of food (kg) that is available for consumption. The amount of food depends on the total population, the expected delivery lead time, i.e., 1 to 15 days, and the amount of agronomic production in the municipalities that depend on the labor of adult and elderly population. Besides, SS2 considers the possibility for food to spoil at a predetermined and fixed rate, assuming that on average, food lasts 15 days before it becomes not suitable for human consumption.

SS3 represents the social structure and demographic behavior of the municipalities, in which three population types are considered: children, adults and elders. Children population is considered to range between the ages of 0 and 18 years old; the adult population ranges from 19 and 60, and elders are considered to have 61 or more years. The age groups were stated to integrate into the model the differences regarding death

rates and food consumption in the three groups. Additionally, this sub-system considers the child and adult migration using estimated rates based on historical data.

3 Experimental results and analysis

Scenario simulations were generated using the software VENSIM® in a Lenovo Y50-70 desktop computer with 12 GB Ram and an intel Core i7@ 2.6 GHz processor. To determine the impact caused by floods and government's reaction speed while facing disaster, three output criteria were considered, i.e., the portion of enabled roads that allow the inflow of goods, total population, and amount of available food (See Figures 1 and 2). Input parameters of Colombia were estimated from the existing data published by DANE (National Administrative Statistic department) (Departamento Administrativo Nacional de estadística DANE, 2020) and Gobernación de Cundinamarca (2016), and Bolivia data from the INE (National Institute of Statistics) and the Instituto Nacional de Estadística (2014). The simulation model considers a horizon of 30 months to allow the system to achieve a steady behavior before a flood related event occurs, allowing the comparison of the expected impact among both populations.

Results show that in both cases, equilibrium is achieved at the beginning of the second month, indicating that during the first ten months there is a stable behavior regarding available consumption and population growth. At the beginning of the 12th month, roads are rendered unavailable due to the impact caused by flooding, hence, there is a reduction in the flow of goods to the municipalities and the amount of available food in two months span, indicating that in both cases the municipalities cannot withstand a flood-related natural disaster without depleting their food supply.

Both populations experienced a measurable impact regarding the amount of available food, Requiring a minimum food stock during the following two months. Additionally, the food arrival rate depends on the fraction of enabled roads given the different estimated government's reaction speed. According to the generated data, Chía tends to recover the full capacity of its roads sooner than Santa Ana.

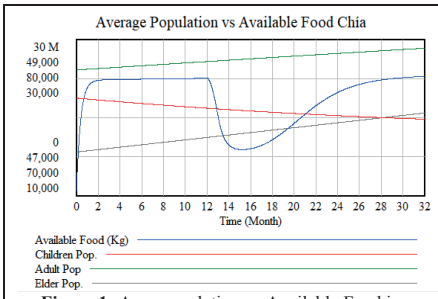

Figure 1: Avg. population vs Available Food in Chía

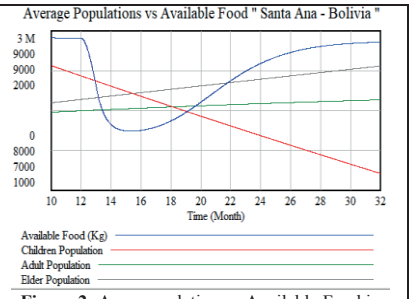

Figure 2: Avg. population vs Available Food in Santa Ana

Regarding the population behavior death rate of infants and elders increases in approx. 0.002% and 0.0023% in Santa Ana and Chía, as seen in Figures 1 and 2. This

phenomenon is explained by the limited resources encountered during the flooding aftermath, however, the increase in death rates does not disrupt the normal behavior of the population's growth and migration.

4 CONCLUSIONS

The proposed method provides a simulation tool for the expected impact assessment of flooding event among populations, allowing to evaluate the time required for populations to regain their normal dynamic. The method was tested in two municipalities located in South America, characterized by flooding risk, especially during the April - June season when the augmentation of the average precipitation levels occurs. According to data, governments' reaction speed supposes the main reason for a fast recovery, indicating the need for governmental entities to design, evaluate and execute different response plans in order to minimize the expected impact among population.

From the obtained results, some interesting new avenues for future research are presented, for example, consider other variables that are also important on this type of disasters, such as the availability and quantity of medical resources and populations' displacement in response to the disaster. Further, the impact of consecutive flooding events within a short period of time, or different preparedness strategies, could also be assessed. Also, we encourage researchers to keep exploring new methods and hybridizing methods for the decision-making process in a humanitarian context.

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Análisis multicriterio aplicado a la selección de un Plan Agregado de Producción

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Resumen. El presente trabajo tiene como objetivo seleccionar el mejor Plan Agregado de producción para una empresa del rubro electromecánico que fabrica tres familias de productos. Para el desarrollo de las alternativas de planificación se adoptan estrategias de nivelación, seguimiento y mixtas. Se emplean como medidas de ajuste transitorio de capacidad la fabricación para inventario, uso de horas extras, subcontratación de parte de la producción y la contratación y despido de personal. La mano de obra es de uso compartido entre las tres familias. Para el análisis de las cuatro alternativas propuestas se analizan múltiples criterios tales como el costo total, la estabilidad de la mano de obra y el plan de producción, los niveles de subcontratación e inventario, considerando las restricciones que pueden existir respecto a los clientes, la fuerza de trabajo y el entorno. Mediante la aplicación del Proceso Analítico de Jerarquías se selecciona la alternativa con el mejor plan agregado de producción para la empresa en estudio. Este plan adopta una estrategia de nivelación de mano de obra, respondiendo al criterio más relevante de mantener la estabilidad de la fuerza de trabajo. La implementación de este método permite materializar el proceso de selección del plan de producción de forma sistemática y consistente con las prioridades estratégicas de la empresa y el área productiva.

Palabras clave: Plan Agregado de Producción, Proceso Analítico de Jerarquías, Toma de Decisiones Multicriterio.

Abstract. The objective of this work is to select the best Aggregate Production Plan for a company in the electromechanical field that manufactures three families of products. For the development of planning alternatives, leveling, monitoring and mixed strategies are adopted. Manufacturing for inventory, use of overtime, subcontracting of part of production, and the hiring and firing of personnel are used as temporary capacity adjustment measures. Labor is shared between the three families. For the analysis of the four proposed alternatives, multiple criteria are analyzed such as the total cost, the stability of the workforce and the production plan, the levels of subcontracting and inventory, considering the restrictions

that may exist with respect to the clients. The workforce and the environment. By applying the Hierarchies Analytical Process, Alternative 1 is selected as the best aggregate production plan for the company under study. This plan adopts a workforce leveling strategy, responding to the most relevant criterion of maintaining the stability of the workforce. The implementation of this method allows to materialize the selection process of the production plan in a systematic way and consistent with the strategic priorities of the company and the production area.

Keywords: Aggregate Production Plan, Analytical Hierarchy Process, Multi-criteria Decision Making.

1 Introducción

La principal función de toda organización es la generación, a partir de ciertos procesos, de algún tipo de producto. Para que estas organizaciones sean efectivas y eficientes los directivos del sistema de operaciones deben comprender y aplicar algunos principios fundamentales de la planificación para la generación del producto y también para controlar el proceso que lo origina.

Para lograr la integración de los procesos organizacionales la planificación y control de la producción debe desarrollarse siguiendo un enfoque jerárquico (Domínguez Machuca et al., 1995). Este enfoque, permite coordinar los objetivos, planes y actividades de los niveles estratégico, táctico y operativo. Significa que los planes de cada nivel persiguen sus propias metas, pero teniendo en cuenta los objetivos de nivel superior, de las cuales dependen y los del nivel inferior, en los que actúan como factor restrictivo. Sin este enfoque es muy difícil lograr la integración de procesos organizacionales.

El Plan Agregado, es un plan de producción a mediano plazo que busca traducir de forma más detallada el Plan Estratégico de la empresa. Su propósito es planificar y coordinar los recursos, incluyendo el tipo, la cantidad y la pertinencia de los mismos, de manera tal de cubrir las necesidades con la demanda prevista (Chapman., 2006).
De una forma más específica es una fuente importante para la planificación de los niveles de inventario, el flujo de efectivo, las necesidades de recurso humanos (número de personas, niveles de habilidad, tiempo requerido, programa de entrenamiento), necesidades de capital, niveles de producción, capacidad, actividades de ventas y marketing.

Para el desarrollo de este trabajo se utiliza el caso de estudio propuesto en el curso de Doctorado “Procesos y Planificación de la Producción Avanzada” de la Universidad Nacional de Cuyo dictado en agosto de 2020.

El objetivo consiste en analizar y seleccionar el mejor plan agregado de producción para la empresa en estudio bajo un enfoque mutlicriterio mediante la aplicación del Proceso Analítico de Jerarquías (PAJ). Este método permite sistematizar y reducir los niveles de riesgo e incertidumbre en el proceso de toma de decisión.

2 Marco Teórico

2.1 Plan Agregado

El plan agregado de producción busca determinar la cantidad y los tiempos de producción necesarios para satisfacer la demanda a mediano plazo. Los administradores de operaciones tratan de determinar la mejor forma de satisfacer la demanda pronosticada ajustando los índices de producción, los niveles de mano de obra, los niveles de inventario, el trabajo en tiempo extra, las tasas de subcontratación, y otras variables controlables.

Por lo general, el objetivo de la planeación agregada es minimizar los costos para el periodo de planeación (Heizer y Render., 2009). Existen, además, aspectos estratégicos como suavizar los niveles de empleo, reducir los niveles de inventario, o satisfacer un nivel de servicio alto a los que se les asigna en ciertas ocasiones, mayor importancia que a la reducción de costos.

El horizonte temporal varía entre 6 a 18 meses, esto depende del tiempo en que la empresa requiera determinar un estimado de la necesidad de recursos, con el objetivo de actuar apropiadamente para garantizar su disponibilidad (Chase y Jacobs, 2014). Con respecto a su diseño, los bloques de tiempo de planificación o periodos de planificación en general son: meses, bimestres o trimestres. Dependerá del nivel de detalle que es útil para la planificación y la cantidad de esfuerzo necesario para obtener la información (Domínguez Machuca et al., 1995).

En el Plan Agregado, como su nombre lo indica, los productos se acumulan o agregan en familias. La clave para efectuar la agrupación es el uso de recursos similares, por ejemplo, el personal, los equipos o las materias primas (Krajewsky et al., 2008). Un motivo fundamental para realizar la agregación es el uso de pronósticos, que son la principal fuente de demanda para efectuar el Plan Agregado y tienden a ser más precisos cuando se desarrollan de forma agregada. Si bien la agregación facilita el desarrollo del plan, no debe llevarse al extremo ya que puede provocar perdida de información útil. El grado de agregación apropiado dependerá del tipo de producto, tipo de clientes, y del proceso productivo.

Con respecto a la capacidad, para esta etapa de planificación se considera fija, es decir que no pueden tomar acciones estructurales de ajuste. Solamente pueden aplicarse medidas transitorias de ajuste de capacidad (Domínguez Machuca et al., 1995).

Las empresas tienen diversas opciones para efectuar un ajuste transitorio de la capacidad. En general, todas estas alternativas se engloban en dos categorías (Chapman, 2006). Una de ellas se enfoca en el lado de la oferta (operaciones) para intentar cambiar el suministro de producción y se las denomina estrategias internas. Estas incluyen las contrataciones y despidos del personal, la contratación de trabajadores temporales, el uso tiempo extra o tiempo inactivo, las subcontrataciones, la fabricación para inventario, entrega con retraso, la posibilidad de no atender la demanda y la modificación de la tasa de producción. La otra categoría se concentra en el lado de la demanda (comercialización) en un intento por alterar los patrones de demanda para ajustarlos al resultado de la producción. Estas son llamadas estrategias externas y consideran la fijación

de precios, la realización de promociones y publicidad y la oferta de paquetes de productos.

2.2 Estrategias del Plan Agregado

Para encontrar la mejor alternativa que organice los recursos y cumpla con la demanda, bajo ciertas condiciones de operación, se debe delinear una estrategia para la elaboración del Plan Agregado. Cuando se habla de mejor, en general, se refiere a la maximización de las utilidades de la organización, pero resulta indispensable que se establezcan otras condiciones u objetivos. Se puede considerar la posibilidad de satisfacer la totalidad de la demanda, minimizar la inversión en inventarios, minimizar el impacto adverso en las personas que puede generar la volatilidad en la fuerza de trabajo por despidos frecuentes, entre otras cuestiones.

Es importante comprender los criterios para delinear una estrategia adecuada que, en general, dependerá de las políticas de la empresa, sus prioridades competitivas, el tipo de sistema productivo, entre otros. Las tres estrategias que se emplean para realizar el Plan Agregado son la nivelación, la persecución o seguimiento y una combinación de ambas (Chapman, 2006).

La estrategia de nivelación busca nivelar determinado recurso (la producción o la mano de obra), es decir, que sus valores se mantendrán constantes en todos los periodos del horizonte de planificación. Esto implica que la demanda fluctúa alrededor de la disponibilidad de dicho recurso, y en su defecto, se harán esfuerzos por alterar los patrones de demanda para que se ajusten de manera efectiva a los recursos establecidos.

La estrategia de persecución o seguimiento altera los recursos periodo a periodo durante el horizonte de planificación. Esto significa que se aumentan y disminuyen sus valores de manera tal de ajustarse a la demanda establecida. Suele aplicarse en entornos donde es difícil alterar la demanda y hay disponibilidad para alterar la base de recursos.

Las estrategias combinadas o mixtas son las más comunes de aplicar. Aquí se mezclan y ajustan las dos estrategias anteriores, nivelando los recursos en algunos periodos y en otros ajustándolos a la demanda.

2.3 Proceso Analítico de Jerarquías

Cuando se requieren utilizar métodos de apoyo a la toma de decisiones en escenarios de múltiples dimensiones de evaluación suele utilizarse el PAJ ya que permite tomar decisiones en base a criterios múltiples. Es un método de trabajo sencillo, lógico y estructurado, basado en la descomposición del problema en una estructura jerárquica (Martínez Rodríguez, 2007).

El proceso requiere que quien toma las decisiones proporcione evaluaciones objetivas y/o subjetivas respecto a la importancia relativa de cada uno de los criterios que se seguirán para tomar la decisión y que especifique su preferencia con respecto a cada una de las alternativas de decisión referida a cada criterio. El resultado del PAJ muestra la prioridad total de las alternativas de decisión respecto a la meta (Toskano Hurtado, 2005)

Para tomar una decisión en forma organizada, es necesario seguir los siguientes pasos (Saaty, 2008):

1. Definir el problema, estableciendo sus componentes o elementos relevantes.
2. Estructurar la jerarquía del problema. Para ello, se elabora una representación gráfica del problema en función de la meta global, los criterios a ser usados y las alternativas de decisión. Se deben identificar los criterios más generales hasta los más particulares. Si se requiere, pueden desprenderse subcriterios. Estos últimos deben guardar una relación jerárquica con el criterio del que se desprenden.
3. Establecer las preferencias: El PAJ, requiere a quien toma las decisiones, señalar un juicio de valor con respecto a todos los elementos de un nivel, referido a cada uno de los elementos del nivel inmediato superior. Se utilizan matrices de comparaciones pareadas para establecer dichas preferencias. Las comparaciones pareadas son las bases fundamentales del PAJ. Se emplea la escala de Saaty con valores de 1 a 9, como se muestra en Tabla 1, para calificar las preferencias relativas de los elementos.

Tabla 1: Escala de Saaty (2008)

Planteamiento verbal de la preferencia	Calificación numérica
Importancia o preferencia absoluta	9
Importancia o preferencia muy fuerte o demostrada	7
Notablemente más importante o preferible	5
Moderadamente importante o preferible	3
Igualmente importante o preferible	1
Valores intermedios	2,4,6,8

4. Priorizar y sintetizar: En un problema jerarquizado, las prioridades pueden ser locales, globales o totales. Una consideración importante en términos de la calidad de decisión final se refiere a la consistencia de juicios que muestra el tomador de decisiones en el transcurso de la serie de comparaciones pareadas. La consistencia perfecta es difícil de lograr ya que los juicios son realizados por personas. Esta metodología calcula la relación o razón de consistencia de Saaty, considerando aceptable los valores menores a 0,1. Por último, se realiza la síntesis del problema para obtener la prioridad total de las alternativas mediante la agregación multiaditiva de las prioridades globales. Esto permite ordenar el conjunto de las alternativas consideradas y seleccionar la mejor alternativa para obtener la meta buscada.

3 Metodología

La metodología adoptada para este trabajo es un estudio de caso. El tipo de investigación es cualitativa y cuantitativa, inicialmente se analizan datos y luego mediante la aplicación de la herramienta propuesta se realizan cálculos matemáticos para selección.

Los pasos a seguir en este trabajo son los siguientes:
1- De manera conjunta entre analistas y expertos de consulta se determinan de las características y necesidades del sistema productivo.

2- Se acuerda también con los expertos, la información relevante para elaborar alternativas para el plan agregado de producción bajo el método de prueba y error con una planilla de cálculo electrónica. Este método es una técnica que funciona considerando todas variables de decisión a la vez para que los planeadores puedan comparar la demanda proyectada contra la capacidad existente. Suele ser muy usado por su facilidad de comprensión e implementación. Si bien no proporciona una solución óptima, es una metodología rápida y sencilla para encontrar una solución satisfactoria de las distintas combinaciones de las condiciones que se introducen al modelo.
Se comparan los resultados obtenidos en las distintas alternativas.
3- Se selecciona el mejor plan mediante la aplicación del PAJ, utilizando como entrada la información generada en los pasos anteriores. El procesamiento se efectúa con el software Expert Choice®.

4 Resultados

4.1 Características del sistema productivo

La empresa en estudio pertenece al rubro electromecánico y se fabrican tres tipos de familias de productos distintos A, B y C. Cada uno de estos productos demandará materiales e insumos en mayor o menor medida. Cada producto para ser fabricado según especificaciones de ingeniería de fabricación, debe pasar obligatoriamente por cuatro procesos agregados, donde en cada proceso hay un tipo de operario con sus herramientas y máquinas necesarias, en el siguiente orden: mecanizados de materiales que conformaran el producto; limpieza y pulidos; ensambles entre piezas y materiales, y ajustes; y pruebas y ensayos finales. En cada uno de esos procesos son necesarios insumos y materiales, los cuales cada uno de ellos se agrupan en familias.

Para cada producto existe un pronóstico de demanda (Figura 1), que es determinista por los pedidos de compras y encargos anticipados, y que hay que cumplir sin postergar entregas en cada mes.

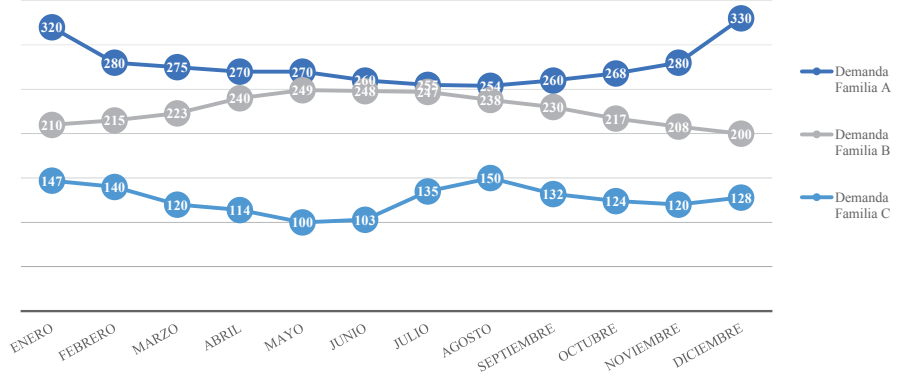

Fig. 1: Demanda determinística anual

Para fabricar cada producto, según los procesos indicados inicialmente, se requiere de los tiempos promedios por cada proceso por operario, estos tiempos se muestran en la Tabla 2. Cada operario trabaja 8 horas a diario, en caso de trabajar horas extras no debe superar las 2 horas extras por día, y al mes no debe superar 20 horas extras. La planta tiene una capacidad para 20 operarios del tipo A; 15 del tipo B; 30 del tipo C y 25 del tipo D, en caso que se requiera contratar más operarios para hacer frente al cumplimiento de la demanda, se debe abrir un nuevo turno de 8 horas regulares para los nuevos operarios que superen dichas cantidades de capacidad limite. Los costos de contratación, despido y hora extras se exhiben a continuación.

Tabla 2. Tiempos de fabricación por operario, costos y plantilla.

Familia de Operarios	Tiempo fab. A (hs)	Tiempo fab. B (hs)	Tiempo fab. C (hs)	Salario mensual	Plantilla fija inicial	Costo Contratación	Costo Despido	Costo Horas Extras
Operarios A	2	1	4	18000	20	40000	60000	150
Operarios B	4	3	7	22000	15	55000	85000	187
Operarios C	3	5	2	25000	26	62000	112000	213
Operarios D	2	1	3	20000	18	45000	95000	170

No hay stock inicial de ninguno de los tres tipos de productos para ayudar en el mes de enero, por lo tanto, se deben fabricar todos a partir de ese mes. En la Tabla 3, se establecen los costos de subcontratar una unidad de producto final terminada, y los costos de mantener una unidad de producto en stock por cada mes que se conserva almacenado.

Tabla 3. Costos de subcontratación y almacenamiento.

Costos	Familia A	Familia B	Familia C
Subcontratación de producto terminado	2300	2200	2450
Almacenamiento de producto terminado	100	85	120

En cada uno de los procesos son necesarios insumos y materiales que se agrupan en familias. Los tipos de insumos son A; B; C y D, y los tipos de materiales que también formarán parte de estos productos son A; B; C; D y E. Cada una de las familias de productos finales demanda una determinada cantidad de cada tipo de familia de insumo y materiales, que es detalla a continuación en las Tablas 4 y 5.

Tabla 4. Costos y requerimiento de insumos.

Familia de insumos	Familia de Producto A	Familia de Producto B	Familia de Producto C	Costo/ Unidad	Stock Inicial	Stock Final exigido	Costo Stock/ Mes
INSUMOS A	2	3	5	25	400	500	1,25
INSUMOS B	3	3	2	102	450	560	5,1
INSUMOS C	1	2	0	68	387	450	3,4
INSUMOS D	4	1	0	35	350	460	1,75

Tabla 5. Costos y requerimiento materiales.

Familia de materiales	Familia de Producto A	Familia de Producto B	Familia de Producto C	Costo/ Unidad	Stock inicial	Stock Final exigido	Costo Stock/ Mes
MATERIALES A	5	0	3	124	201	580	6,2
MATERIALES B	2	1	5	201	408	570	10,05
MATERIALES C	1	2	4	154	389	600	7,7
MATERIALES D	0	4	3	186	652	620	9,3
MATERIALES E	6	4	2	27	501	480	1,35

4.2 Alternativas del Plan Agregado de Producción

Con el objetivo de seleccionar el mejor Plan Agregado de producción se elaboran cuatro planes alternativos, siguiendo diversas estrategias y medidas de ajuste de la capacidad. A continuación, se describen los lineamientos adoptados en cada una.

- **Alternativa 1:** Esta alternativa propone la implementación de una estrategia de nivelación de mano de obra, tratando de abastecer la totalidad de la demanda durante cada período de planificación. Las alternativas de capacidad aplicadas para alcanzar los objetivos establecidos son el uso de horas extras, la generación de inventario, la subcontratación y la contratación y despido de la fuerza de trabajo. La mano de obra es de uso compartido entre las tres familias de producto y se establece un nivel de fuerza de trabajo constante por tipo de operario durante todo el periodo de planificación. De esta manera, existen meses con tiempos ociosos de trabajo que se utilizan para fabricar inventario y evitar los quiebres de stock y la reducción de necesidad de subcontratación.
- **Alternativa 2:** Este plan se realiza siguiendo una estrategia combinada de nivelación de las cantidades a producir en cada periodo del horizonte de planificación

con una nivelación de mano de obra. Se emplean como medidas de ajuste transitorio de capacidad la fabricación para inventario, uso de horas extras, subcontratación de parte de la producción y la contratación y despido de personal. Se considera que la mano de obra es compartida entre las tres familias, para cada etapa del proceso productivo. Las horas de trabajo ociosas se las utiliza para producir inventario para evitar el desabastecimiento de la demanda y la reducción de la cantidad de productos a subcontratar. La nivelación de la mano de obra se realiza en dos tramos. Durante el primer semestre, se establece un nivel mayor de mano de obra para generar inventario mediante la utilización del tiempo ocioso y durante el segundo semestre se establece un nivel de mano de obra menor.

- **Alternativa 3:** El plan se realiza adoptando una estrategia de persecución donde se produce la cantidad de unidades requeridas para abastecer la demanda. Esta estrategia no genera inventarios y la mano de obra es de uso compartido entre las tres familias de producto. Las alternativas de ajuste de capacidad aplicadas son la contratación y despido de la fuerza de trabajo, el uso de horas extras y subcontratación.
- **Alternativa 4:** El plan que propone se obtiene mediante una estrategia de persecución combinada con una estrategia de nivelación de mano de obra. Durante un periodo del horizonte de planificación se nivela la mano de obra, mientras que se ha hecho uso de una estrategia de ajuste al momento de absorber las necesidades de los periodos de demanda alta. La mano de obra es de uso compartido entre las tres familias de producto. Las alternativas de ajuste de capacidad aplicadas son la contratación y despido de la mano de obra, generación de inventario, uso de horas extras y subcontratación. Se busca minimizar la cantidad de horas ociosas mediante la producción para inventario con el fin de evitar el desabastecimiento de la demanda y la reducción de la cantidad de productos a subcontratar.

El motivo de tratar de minimizar la subcontratación se debe a que el costo variable unitario de las tres familias reporta un valor superior en relación a la fabricación en horas regulares (28%) y horas extras (31%).

4.3 Comparación de Alternativas

En la Tabla 6, se presentan los costos asociados a las alternativas de Plan Agregado de producción propuesto para las tres familias. Los cuatro planes alcanzan un nivel de servicio del 100% ya que no se producen quiebres de stock en ningún periodo y de esta manera se logra abastecer la totalidad de la demanda. La alternativa 2 es la que menores costos genera, sin embargo, se puede apreciar que en todos planes los costos más representativos son los de materia prima, mano de obra regular y contratación y despido. Los costos de horas extras, inventario y subcontratación obtienen valores menos significativos respecto a los anteriores.

Tabla 6. Costos asociados a las alternativas del Plan Agregado

Alternativa	1	2	3	4
Costo HR	$ 11.568.000	$ 10.890.000	$ 10.898.000	$ 10.922.000
Costo HE	$ 776.524	$ 877.158	$ 732.998	$ 762.835
Costo Subc.	$ 90.650	$ 95.550	$ 346.400	$ 314.600
Costo Cont./Desp.	$ 3.109.000	$ 3.488.000	$ 4.565.000	$ 3.836.000
Costo Inventario	$ 263.185	$ 122.610	$ 0	$ 94.275
Costo MP	$ 16.860.904	$ 16.007.883	$ 15.868.801	$ 16.046.154
Costo Total	$ 32.668.263	$ 31.481.201	$ 32.411.199	$ 31.975.864

En la Tabla 7 se presentan los indicadores de desempeño más significativos para el análisis de cada plan. El coeficiente de variación de la mano de obra y del plan de producción se considera con el objetivo de comparar la estabilidad que proporciona cada plan. La alternativa 1 presenta la menor variabilidad de la mano de obra y la alternativa 3 la menor variabilidad del nivel de producción. Asimismo, se presenta el porcentaje de inventario y subcontratación de cada plan respecto a la producción total para los diferentes planes presentados. La menor generación de inventario se obtiene en la alternativa 3 y la menor subcontratación se realiza en la alternativa 1.

Tabla 7. Indicadores de desempeño por alternativa

Alternativa	CV MO	CV Producción	% Inventario	% Subcontratación
1	0%	6,77%	33,75%	0,47%
2	3,80%	5,78%	15,84%	0,52%
3	4,99%	3,00%	0,00%	1,88%
4	3,81%	8,87%	13,15%	1,75%

4.4 Selección del mejor Plan Agregado

Para comenzar el PAJ se elabora la estructura jerárquica del problema planteado. Se determina como meta global "Seleccionar el mejor Plan Agregado de Producción" y se establecen como criterios más relevantes para tomar esta decisión los costos totales del plan, la estabilidad de la mano de obra, estabilidad del plan de producción, el nivel de inventario y el nivel de subcontratación. Estos se evalúan en forma cuantitativa, considerando los resultados presentados en las Tablas 6 y 7.

Se pretende encontrar la mejor alternativa que reporte menores costos a la empresa. Los criterios de estabilidad de la mano de obra y del plan de producción apuntan a reducir los porcentajes de variabilidad de ambos factores. Una menor variabilidad en la fuerza de trabajo genera un impacto positivo en su motivación y moral y en consecuencia en la eficiencia y efectividad de su trabajo. Por su parte, un plan estable proporciona facilidades en su gestión e implementación.

Respecto al criterio de nivel de inventario, se toma como mejor solución aquella alternativa en la que se reporte una menor generación de inventario debido a los requerimientos de espacio y recursos necesarios para su gestión y guarda.

El criterio de nivel de subcontratación proyecta medir el riesgo estratégico que supone la tercerización de la producción y se intenta minimizar su valor.

A partir del establecimiento de la meta global y la definición de los criterios de decisión, se presenta en la Figura 2 la estructura jerárquica del problema.



Fig. 2: Estructura Jerárquica

Mediante reuniones de trabajo con el grupo de analistas y expertos se determinan las preferencias respecto a la prioridad de los criterios y las alternativas de decisión en relación a cada criterio de selección. Estas valoraciones se ingresan al software Expert Choice® y se obtienen las prioridades locales y globales y la consistencia de los juicios.

En las Figuras 3 y 4 se presentan pesos de los criterios de selección y la priorización final de las alternativas, con el índice de inconsistencia, indicativo de la coherencia de los juicios.

Fig. 3: Pesos de los criterios

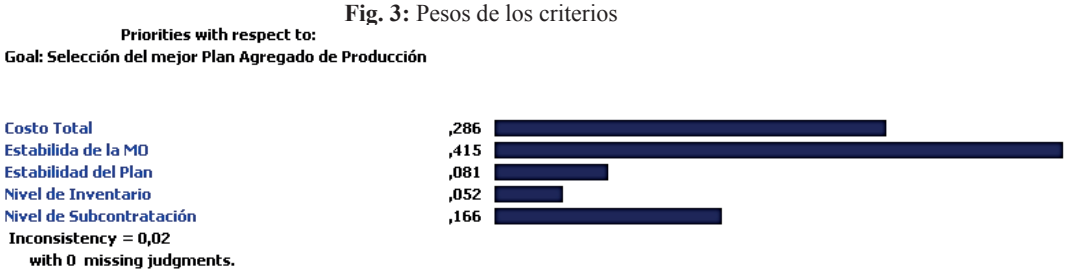

Fig. 4: Priorización de las alternativas



Se evidencia que los criterios más importantes son la estabilidad de la mano de obra (41,5%) y los costos totales (28,6%), seguidos por el nivel de subcontratación (16,6%), estabilidad del plan (8,1%) y el nivel de inventario (5,2%)

Como resultado final, se obtiene que la Alternativa 1 es la mejor con una prioridad total del 37%, seguida por la Alternativa 2 con un 31,4%, la Alternativa 4 con 17,3% y finalmente la Alternativa 3 con un 14,3% de prioridad.

Se corrobora que todas las matrices de comparación pareada son consistentes, obteniendo un valor de consistencia global de 0,02. De esta manera, se verifica la calidad de la decisión final ya que los juicios del tomador de decisiones son consistentes en todo el proceso de análisis jerárquico.

5 Conclusiones

La implementación del PAJ permite la estructuración del problema de selección de un Plan Agregado de Producción factible en forma sencilla, teniendo en cuenta criterios de selección acordes con las prioridades estratégicas del área productiva y de la empresa en estudio. Los criterios más relevantes para el proceso de selección son la estabilidad de la mano de obra y los costos totales que genera la implementación del plan.
Se plantean cuatro planes como alternativas viables a implementar. Todos logran abastecer la demanda prevista al presentar un nivel de servicio del 100% para las tres familias de producto. Se utilizan como opciones de ajuste de capacidad el uso de horas extras, la generación de inventario, la subcontratación y la contratación y despido de la fuerza de trabajo.

Respetando los criterios y restricciones establecidos se obtiene una jerarquización de los cuatro planes considerados y se selecciona uno de ellos, alternativa 1, como el mejor Plan Agregado de Producción. El plan correspondiente a esta alternativa aplica una estrategia de nivelación de mano de obra, reportando una ventaja significativa a la empresa, ya que proporciona una estabilidad total a la fuerza de trabajo al establecer un plantel constante durante el horizonte de planificación. Asimismo, la estabilidad de la fuerza de trabajo logra evitar el impacto negativo en la motivación y moral y en consecuencia en la eficiencia y efectividad de su trabajo. También permite reducir los problemas derivados de las restricciones o presiones que puedan proceder del entorno empresarial como pueden ser las regulaciones contractuales o actividad de los sindicatos no deben ser minimizadas a la hora de definir los niveles de mano de obra del plan.

La metodología propuesta permite a la Gerencia de producción efectuar el proceso de planificación de la producción de forma sistemática y consistente con las prioridades de la empresa. La utilización de Expert Choice resulta amigable y soluciona la selección de la alternativa de planificación más conveniente en función de los criterios utilizados y sus preferencias relativas. Si bien las hojas de cálculo electrónicas no proporcionan soluciones óptimas, resultan herramientas sencillas y de fácil comprensión para la elaboración de plan agregado ya que es posible incorporar y relacionar todas las variables de decisión que intervienen en el proceso.

Se concluye que la metodología multicriterio propuesta, en particular PAJ, es de factible y eficaz implementación para la empresa. Factible, en tanto utiliza datos de entrada que son derivados de la actividad habitual del proceso de gestión de la producción; y eficaz porque permite obtener el mejor Plan agregado que logra combinar los

recursos de manera tal de satisfacer la demanda prevista y considerar los criterios establecidos en función de las características y necesidades de la empresa.

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A Computer Vision based Gaze Following Application: Contribution in COVID-19 Scenario

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Abstract. The level of attention of workers in their diary activities is an important factor to keep the quality of production and its own safety. Computer vision based tools can improve the human support by supervising handled operations by cameras and image analysis. In this context, the gaze following estimation is useful to detect if someone is looking in the right direction and keeping their focus of attention in the predictable time. Due pandemic COVID-19 times, we developed an adapted device and a computational tool based on deep-learning to detect if a person is looking to a temperature measurement device who enable or deny access to their workspace. We present the method architecture in context of Industrial Internet of Things (IIoT) to a real-life application as an automated solution to access control. It is also presented the quantitative data analysis from measurement tests performed at factory entrance and it is pointed future perspectives of improvement of proposed method.

Keywords: Gaze Following, Computer Vision, Deep Learning, COVID-19

1 Introduction

The recent event called Covid-19 pandemic worldwide, brings necessity to productive and service sectors rethink actions and to look for self-adjustment procedures to continue its operation in the new reality.

Gaze following based on computer vision is a useful tool to infer attention level from someone over its routine activities [1]. The non-contact measurement device, as cameras, leaves someone comfortable in its own workspace and capture reliable data according its movements and intentions. In retail, for example, they can infer consumer interest in different display items based on human-object eye contact in real time, seeking to understand consumer interest in different focuses of attention, such as price, packaging, average time look, or the items that attracted the most in the window. At the same way, into classroom activities the interaction among students and teacher can be measured to identify who is paying attention to some specific activity [2],[7-8]. Other important application to gaze-following is to protect operator's

healthy in shop-floor routinely tasks, by measuring the attention level of a specific assembly/disassembly task, or by handling dangerous equipment or materials, in order to identify concentration debility or stress issues.

In this work, the term gaze following (GF) refers to the "focus of attention" that means the direction in which the person is looking (object which someone is fixing in the look [1],[3]) in terms of its head position. We apply the GF concept to measure if a person is looking to a thermometer device in order to enable him to access a factory plant. In this way, the process to temperature measurement can be automatized replacing a people dedicated to proceeding the measurement in order to avoid contact a face-to-face. By this way, a vision-based system brings guaranties to identify a person by facial recognition and to give access permission to his local of work. Figure 1 shows the conceptual idea of proposed method.

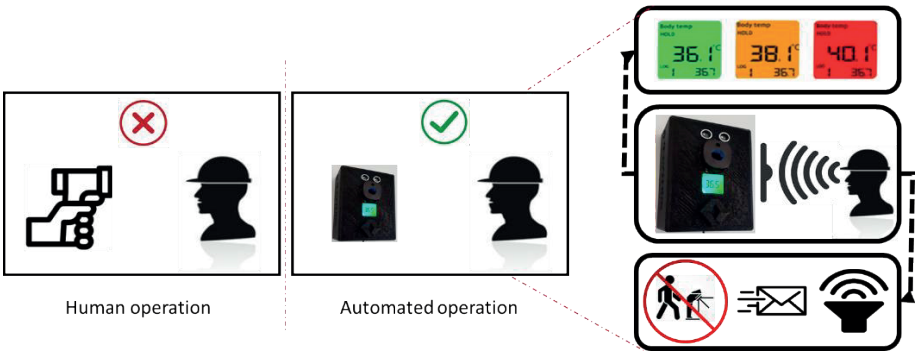


Fig. 1. Conceptual sketch of proposed method.

According fig.1, the infrared pistol type thermometer can be replaced by a wall fixed device with the same function of head temperature measurement without proximity with a human operator. The proposed approach is an AI supported software associated to a computer vision system to guaranty the data gathering veracity. The kernel of system are the computational algorithms based on convolutional neural networks (CNN) to explore facial recognition, head pose estimation and gaze direction. The literature supporting this approach is given in the next section.

2 Background

The literature used as basis of conceptual understanding about gaze following was conducted by the research development methodology who includes: (i) Systematic Literature Review (SLR) and content analysis, and (ii) experimental procedures. The purpose of the review is to identify which are the main requirements for the application of vision systems and which are the most efficient AI techniques for implementing a gaze-following tool applied for temperature measurement test to enable or deny access the working area in a factory.

It is proposed to carry out the systematic literature review as in [4] and modified as presented in [5]. The modified m-SLR merges content analysis and regression analysis tasks in a single step. The content analysis stage filters the results of the research, providing a more precise perspective of the researched topic, while the regression analysis increases the robustness of the selected articles, adding statistical evidence for the selection of the articles.

Trending topic keywords can result in many documents being evaluated by content analysis, and many of them may not be related to the desired topic. To minimize this effect, Latent Semantic Analyzes (LSA) is applied to the text mining procedure, as proposed by [6], which is the language processing technique (NLP), followed by a reduction in dimensionality based on the decomposition of singular values (SVD).

After applying this methodology with content analysis over many documents, we found the following articles currently considered the actual state of the art by the use of deep learning and computer vision techniques for gaze following and given support to this research. They are:

i. Recasens *et al.*[7-8], proposed a convolutional neural network (CNN) architecture whose pipeline is divided in two different paths, where one is dedicated to discovering salient points in the image (as target of view) and the second path determines the head pose. Thus, to determine a Gaze Pathway, the pipeline receives as input only the cut image of the head and its location. Then, first apply the convolution layers to the image of head, and after it concatenates the result of the convolution with the position of the head and use them as input to row fully connected layers. Finally, a sigmoid activation function is used to generate results between 0 and 1 producing a heat map (*gaze mask*) of a region that is the attention focus.

ii. Lian *et al*. [2] presented a new and more intuitive approach to gaze following estimation, composed by two steps. In first, the image of head and its position in image is used to an initial estimative of several field of gaze, and the gaze following is coded in different scales. In the second stage, those all fields of gaze are concatenated together original image, and thus serving as input to a regression model as in [9]. The gaze-following datasets are annotated by a third person and the proposed model is used in a real scenario the authors proposed an specific metric called *MAng*, minimum angular error that measures the minimum angle between the predicted point and the annotated truth (*ground truth*). Thus, it was created a new dataset called Daily Life Gaze dataset (DL Gaze) of videos annotated by the people who were on the scene in order to obtain a more accurate ground truth. In this way, it is possible to infer the accuracy of the proposed model in everyday scenes.

iii. Ruiz *et al*. [10] combined the neural ResNet50 [11] with a multi-loss architecture, where each loss contains a combined classification and regression, which correspond to the yaw, pitch and roll angles individually. Obtaining robust results, his proposal to classify the head position was named HopeNet.

iv. Yang *et al.* [12] proposes a method based on the TensorFlow [13] deep learning framework that improves the previous methods based or not on the marking of points on the face for estimating head positioning (*head pose estimation*). It stood out for its high capacity to determine the head angulation in a wide range of positions and even with partial occlusion of the face. It is due on the fact that the proposed architecture does not use the points of the face to determine the angle of the head.

v. Kellnhofer *et al.* [14] present a large-scale gaze-tracking dataset (the Gaze360) and a method for robust 3D gaze estimation. The dataset consists of subjects in indoor and outdoor environments with labelled 3D gaze across a wide range of head poses and distances. They introduce a discriminator which tries to identify the source domain of the image features as a binary classification task. The features are the output of the backbone network (ImageNet-pretrained ResNet-18 [11]). The discriminator loss is added to the original supervised loss for those images where ground truth is available. Thus, this approach is suitable for deep learning of 3D gaze from images and video.

Following SLR, we conduct an experimental procedure to evaluate the literature based models and proposed an application method to assess the gaze field from subjects looking at temperature measurement device in order to identify subjects with possible fever symptom related with COVID-19 as presented in next sections.

3 Proposed Method

An application structure is proposed according steps indicated in fig.2. It is shown four subsequent processes that deals about the subject detection, gaze direction measurement, temperature measurement and access permission.

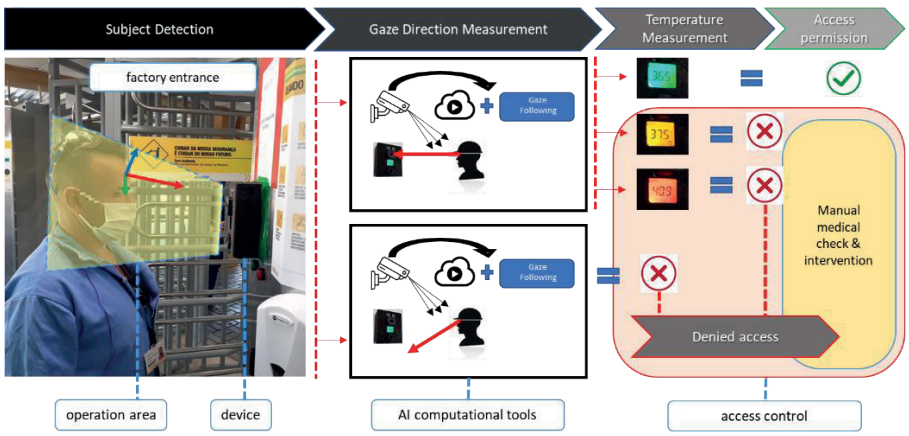


Fig. 2. Functional blocks of proposed method.

According fig.2, the functional blocks are:

Subject detection: the first step is to proceed the subject detection. Due safety protocols have been applied during COVID-19 pandemic restrictions; the factory entrance lines were organized so that it exists distance regulations between individuals. Immediately in front of each entrance, it was set up the sensing device. The individual must stand in front of device in a maximum range of 50 cm between device and user measured by an ultrasound sensor. The measure will be taking only if the correct gaze direction is detected.

Gaze Direction Measurement: This is a system feedback step and it remains active while the subject is not correctly positioned in front of sensor device. Once correct gaze direction is identified the temperature measurement is triggered.

Temperature Measurement: After correct head pose estimated and gaze direction detected, an infrared sensor measures the temperature from subject's head. According nominal value measured is less than threshold value (for instance, 37.5°C) an information is passed to access controller of gate who provide autonomous action to open or not the gate.

Access Permission: if the temperature measured is equal or above thresholding value, device sounds a beep, a message is sent to the medical staff and gate is blocked until next subject from line takes his temperature. The subject should go to specific place on entrance to manual verification and medical procedures.

3.1 Hardware specification

The hardware prototype is powered by a 9V DC switching source and can be analyzed in three distinct parts: the detection circuit, the temperature measurement circuit and the alarm and notification circuit, with all of them connected by a microcontrolled board.

For the control, an Arduino UNO development board kit is used, which has an ATMega328P programable microcontroller, with a digital and analog data input and output system, capable of interacting with components and devices connect-ed to it.
For the detection circuit, we embedded a low-cost ultrasonic sensor, model HC-SR04, consisting of two transducers, an emitter and a receiver operating at 40kHz that matches with our purpose of no long-range readings [16]. The distance evaluation is managed through the development board that evaluates the time from the exit until the return of the emitted ultrasonic signal, considering the speed of the sound signal in the air of approximately 340m/s.

To temperature measuring, we embedded an adapted commercial thermometer. The infrared sensor captures the waves, converting them through its own circuit into an analog signal that, after conversion to the Celsius scale, is shown on the equipment's display, which is distinguished by the colors green, yellow and red, in this sequence of temperature's scale.

To make an accurate reading of the temperature, the sensor was calibrated with a distance of 50cm. Measures below this value cause the Arduino to send a 5V signal to the base of the NPN TIP41C transistor, saturating it, causing it to activate the button

(trigger) of the temperature measurement circuit. The nominal value and the signal responsible for the changing colors were used as input to the Arduino, which generates alerts through its digital and analog pins for the third circuit of the device.

The alarm and notification circuit have an audible alarm and a lamp informing the security professional which device has high temperature signals. The user, likewise, receives these signals more discreetly on the device, in addition to being denied access to the factory. The analog signal is used in conjunction with an ESP8266 module, which is a microcontroller device with Wi-Fi communication capability with an integrated TCP/IP protocol [17]. This module is used integrated with Arduino, sending emails to a list of company supervisors.

Figure 3 presents a block diagram that describes the device and its circuits. It also shows the sequence of its operation.

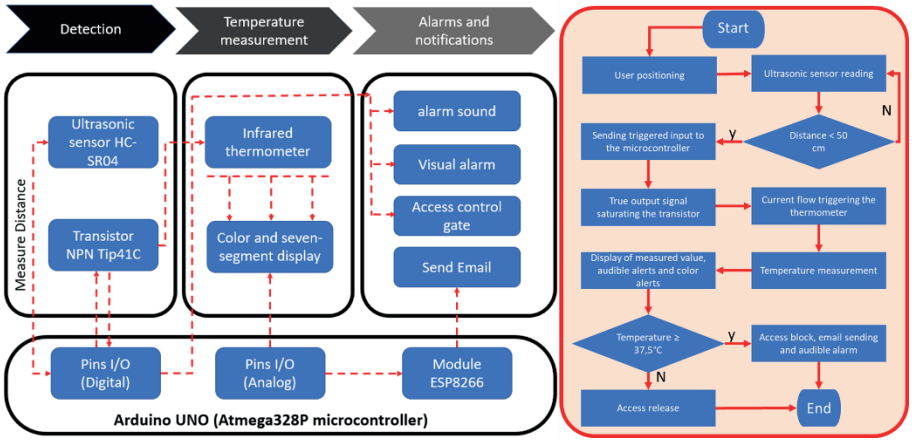


Fig. 3. Hardware components diagram.

In order to guaranty the correct head position to temperature measuring, we configurate the environment with a digital camera to capturing images from each one posed in front of device. From image it is possible to get the direction where people are looking, that is, if its gaze is on the device as target. Thus, a gaze following algorithm was implemented to work together with measuring device.

3.2 Gaze Following Pipeline

The task of determining the gaze direction necessarily requires face detection procedure. Automatic face detection is a prerequisite in several computer vision systems, which aims to detect and estimate bounding boxes at different scales of size and face positions. The algorithm to determine the gaze direction presupposes the existence of the starting point of interest in the field of vision. Thus, the flowchart presented in figure 4 present the sequential steps to a gaze following pipeline.

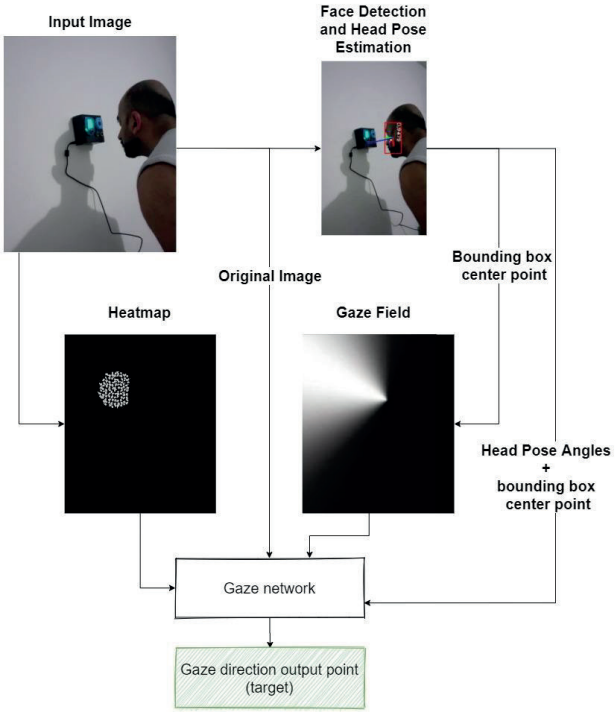


Fig. 4. Gaze following pipeline.

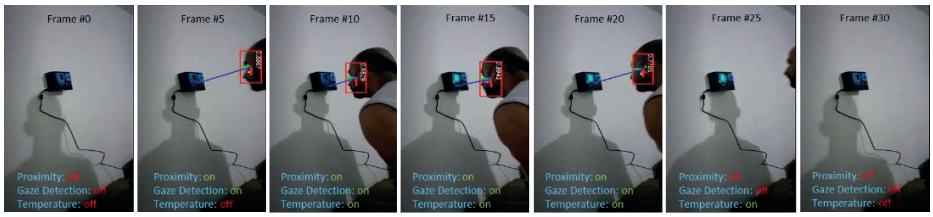
As the first stage of the pipeline, the image is processed by a neural network for facial detection. The model adopted for the first stage was the RetinaFace [15]. Then, as proposed by [1], with the result of the first stage of the pipeline, the position of the head is estimated from the cut of the face detected in the image. Then it determines the position of the head, as proposed by [10], which results in three axes (pitch, yaw and roll) whose values serve as input for the second step.

We consider as origin of coordinate center of gaze the center of the face's bounding box. The field of vision direction is generated with the point of origin of the look, called gaze field (in figure 4). Thus, the data to determine the direction of gaze, was performed by a neural network model that receives as input parameters: (i) the angles resulting from the estimation of the position of the head, (ii) the original image, (iii) the field of direction of the look (gaze field) and (iv) the gaze point origin.

The gaze target is determined by the neural network (Gaze Network) proposed in [1]. The output is activated by a sigmoid function that generates values in the scale of 0 to 1 in the same size as the input image. Thus, it is possible to present a heat map image of the possible targets of the subject eyes. The higher value among all of heat map resulting from the merging of data in the Gaze Network is considered the target point to build a line of view. In this way it is possible to determine the direction of the gaze and also its respective target. The heat map is an important output to results monitoring of the Gaze Net neural network [2].

4 System Evaluation

A test was performed to gaze following evaluation in a controlled indoor laboratory environment in order to measure the system accuracy and to find all associated possible errors. Fig.5 shows a frame sequence for an automated measuring experiment.



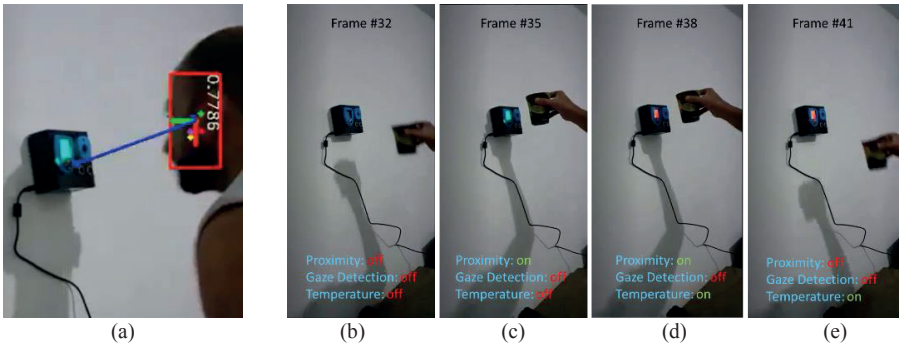
(a) (b) (c) (d) (e) (f) (g)

Fig. 5. Frame sequence for gaze following and temperature measurement testing.

In fig 5.(a) the sensor device is in idle state, waiting the detection of someone; in (b) and (c) the proximity of presence of an individual was detected and the gaze direction is also detected but temperature is not measured until the correct direction vector (yaw, pitch and roll) is out of expected angle range. In (d) and (e) the temperature is taken and displayed to user. In (f) the user moved away after the temperature value displayed, and the gaze vector does not appear after distance increased. In (g) the system come back to idle status. Thus, in this controlled environment, the detection and measurement work in correct way about 100% of all performed tests.

The detail of head position based detection is present in fig.6(a). The coordinate system orientation is determined by gaze following pipeline according method of [1]. The bounding box circumscribe the detected face.

The strength of method permits detection from partial face (or partial occlusion) in image.



(a) (b) (c) (d) (e)

Fig. 6. (a) Head identifying; (b)Simulation with no head detection and using a hot coffee cup. (c) proximity detected but still without temperature measurement. (d) temperature measured and displayed. (e) cup withdraw and temperature display remaining on with configurable time.

In Fig.6(b) to Fig.6(e) a test was performed using a hot coffee cup, and as expected there are not gaze detection because a human face does not exist in image. Also, the temperature was measured to check the different values displayed and to validate the threshold value.

5 Case study

As a case study was carried out in a real factory scenario. The equipment was placed in a testing phase in one of the access gates, as presented in fig.7.



(a) (b)

Fig. 7. Real environment configuration

The effectiveness of the response obtained during three testing sections at the time of entry of the workers rotation, where there is the major number of subjects circulation at same time, is presented in table 1.

Table 1. Results of testing during a sampling period.

	testing sections			**total**
	1	2	3	∑
Monitored volunteers	82	65	70	217
Fever symptom detected	1	3	0	4
Incorrect user pose (#)	7	5	6	18
Incorrect user pose (%)	8.5	7.7	8.6	8.3
Detection failure (#)	4	3	3	10
Detection failure (%)	4.9	4.6	4.3	4.6

From the experiment, 217 people were monitored in one single gate, where 4 showed signs of fever and were leaded to the health sector. The table 1 shows results where: (i) The number of incorrect user pose is when the algorithm detected the per-

son, however, the user was not looking at the equipment. This situation occurred in about ~8% of detections. (ii) the detection failure considered the situations in which the user had his face recognized, but the look has not been identified, or those all cases where neither the face has been identified. This situation occurred in about ~4,5% among all detections. Of course, in all cases when detection is incorrect (or uncertain) the gate remains closed. In this case the person should go to a manual screening to testing. Or of course, try again in another gate do get access.

Assuming that the factory plant has around 7,500 employees and with 4 main entrances with 8 gates, the projection of the gain is that around of 13% needs to be retested by a manual way. Thus, in this way, it is possible to reduce from 32 employees to just 1 operator by entrance with manual thermometer to retest operations.

6 Conclusion

This research presented a gaze following method applied to a real situation on COVID-19 scenario. A sensing device was built in order to automate the process of temperature gathering without human intervention on measures. The contribution given by automatization of process allow a useful reduction of workers exposure to direct contact to making the manual measures.

By complementary way, a software was developed to management and system operation based on computer vision and artificial intelligence algorithms. In this context, a gaze following pipeline was proposed to certify the correct gaze direction of head position; and if it is correctly detected a trigger enable the temperature measurement. After that, according value measured a threshold enable or denies the access to factory plant.

The tests carried out demonstrated the importance of an efficient face detector model in the pipeline. Given the current situation of COVID-19, people are always wearing masks and failure to detect the face will cause the pipeline to break. The model adopted from [15] did not present limitation in detecting faces in images form subjects wearing a mask in the tests performed, as shown in evaluation table 1.

Some improvements can be developed, as for instance, face recognition to automatization of identifying possible ill subjects, identification of users without wearing mask or without sanitize his hands, message dispatch to managers and medical staff among other facilities.

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A production planning MILP optimization model for a manufacturing company

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Abstract. This paper proposes a mixed-integer linear programming (MILP) model that is implemented based on a rolling horizon scheme to solve an aggregate production planning decision problem of a manufacturing company that produces snacks in Monterrey, Mexico. The demand of the company is characterized by trends and seasonality. The proposed solution is evaluated by means of computational experiments to determine the relation between demand uncertainty and flexibility of a production system. A 2^k factorial experimental design and a multivariate regression were performed. Results show forecast bias and length of frozen period in the rolling horizon have a strong effect on total profit. The safety stock level was also found to be a significant factor, depending on the level of bias.

Abstract.

Keywords: Production planning · Rolling horizon · Forecast error · Flexibility factors

1 Introduction

This study considers a production planning problem for a snack factory located in the metropolitan area of Monterrey, Mexico. The company has presented significant costs due to high inventories, overproduction, and stockouts. Executives consider that the company experiences a bullwhip effect due to the lack of a precise forecast and an assertive communication between departments in the company. This can be also a problem related to the flexibility of the production system of the company, as even in the cases in which forecasts have a good accuracy, the company does not achieve the desired results. The company operates like this. The production manager receives a demand forecast estimated by the sales department. Then, the production manager defines an aggregate production plan every month, and that plan is executed on a weekly basis by sales and production departments. The level of uncertainty and

variability of the demand of the company are important factors to be considered for their planning operations. This uncertainty can be related to sales, prices, technology development, etc.

One strategy that can be employed to modeling the decision-making process of the production manager is by means of a rolling horizon scheme [14]. Unlike a fixed-horizon production planning process, in a rolling horizon strategy demand forecasts are updated every iteration of the planning horizon [10]. Hence, under a rolling horizon planning scheme, several different optimization sub-problems are solved considering a forecast of demand. After the realization of the demand, the resulting plans are updated, and the iterations continue until the production plan for the entire planning horizon has been determined [1].

Based on the characteristics of the company considered as a case study, a mixed integer linear programming model is proposed, to support the production planning decisions of the company. The proposed model is implemented considering a rolling horizon scheme. A set of experiments is conducted to evaluate the mathematical relation between demand forecast errors and the flexibility of the production system.

The remainder of this paper is organized as follows. Section 2 presents a literature review regarding districting problems. Section 3 presents the proposed mathematical formulation and solution approach. Section 4 describes the experimental design and Section 5 discusses the analysis of results. Conclusions and recommendations for future research are given in Section 6.

2 Literature review

Production planning is an area of great interest for both practitioners and academics. Since the pioneering studies that proposed linear decision rules and suggested some basic applications methods, innovative models and solution methodologies to handle these problems have been proposed in the literature. Jalmania et al. [5] present a comprehensive literature survey and future research directions for aggregate production planning problems under uncertainty. They analyze and classify the literature and identify future research paths, highlighting that few studies on rolling horizon implementations for aggregate production planning can be found in the literature, in both the deterministic case and the case under uncertain conditions.

Among the contributions that consider a rolling horizon for Aggregate Production Planning (APP) models, we can mention the study conducted by Demirel et al. [1]. They proposed a mixed integer linear programming model under a rolling horizon scheme with flexibility requirements where demand is regarded as an uncertain variable. Jain and Palekar [3] and Hahn and Brandenburg [2] consider the APP in process industries. The former contribution develops a stochastic linear programming method to study APP with resource limitation considerations in a continuous food producing company. The latter contribution develops a sustainable APP decision model for a chemical process industry by applying stochastic queuing networks. Only Jain and Palekar [3] consider a rolling horizon implementation.

Lin and Uzsoy [7] use two different chance-constraint formulations to reduce planned release changes while maintaining a desired service level under stochastic demand in a rolling horizon environment and compare them with an LP formulation that does not consider uncertainty. Vogel et al., [11] develop a hierarchical and an integrated model considering two levels of hierarchical production planning, the APP and the Master Production Scheduling (MPS), in order to show that it is possible to integrate them into a single model and, at the same time, fulfill their requirements. The interaction of both levels was implemented on a rolling horizon approach. Li and Ierapetritou [6] propose a methodology to derive the production capacity constraints based on short-term scheduling model through parametric programming technique and use this capacity information in the rolling horizon framework to improve the final solution's quality.

Zhang et al., [14] develop a two-stage integer stochastic planning model for an international enclosure manufacturing company with seasonal demand and market growth uncertainty. The model was implemented considering different solution methodologies, including two rolling horizon algorithms, comparing their performance. Sitompul and Aghezzaf [8] propose a preventive maintenance model that considers a non-cyclical planning, which means that the preventive maintenance periods do not necessarily fall at equally distant times. They solve the problem at the detailed level using a rolling horizon approach and calculate the average of the total costs at the detailed level. Stephan et al., [9] propose a multi-stage stochastic dynamic programming method to support real world capacity provision and adjustment decisions in automotive manufacturing networks. They compared their proposed methodology with respect to a rolling horizon two-stage stochastic planning approach. Wu and Ierapetritou [12] present a hierarchical approach for production planning and scheduling under uncertainty, using a multi-stage formulation. The optimal schedule is determined using a rolling horizon strategy. Yao et al. [13] address a medium-term capacity and production planning model to plan and support production operations for meeting multiple product demands considering a multi-facility manufacturing system. The system has limited product flexibility, and, continuous and discrete capacity change options with varying implementation time and cost. For testing, the MILP problem approach was implemented with a rolling horizon schedule as solution method in practice.

Table 1 summarizes in chronological way the most related contributions to this work, including those previously described. The table classifies the contribution with respect to the type of model proposed, the solution methodology and the type of planning horizon (fixed or rolling one). The last row corresponds to the contribution presented by this manuscript.

Table 1. Related literature on production planning models under uncertainty

Publication	Modeling approach			Solution methodology			Planning Horizon	
	I	II	III	A	B	C	1	2
Jain and Palekar [3]		X		X				X
Wu and Ierapetritou [12]			X	X				X
Li and Ierapetritou [6]		X				X		X
Stephan et al. [9]			X	X				X
Sitompul and Aghezzaf [8]			X	X				X
Zhang, et al. [14]			X	X				X
Lin and Uzsoy [7]	X			X				X
Vogel et al. [11]		X		X				X
Hanh and Brandenburg [2]			X			X	X	
Jamalnia et al. [4]			X	X			X	
Jalmania et al. [5]		X	X	X	X		X	X
Demirel, et al. [1]		X		X				X
Yao, et al. [13]		X				X		X
Cedillo et al. (This work)			X	X				X

[I] LP [II] MILP [III] Stochastic; [A] Optimization [B] Simulation [C] Heuristics; [1] Fixed Horizon [2] Rolling Horizon

3 Mathematical Formulation and solution approach.

In this section we present the mathematical formulation for the aggregate production planning problem (Section 3.1) and the solution approach based on a rolling horizon scheme (Section 3.2).

3.1 Mathematical Formulation

In this paper we consider a manufacturing company that produces set of I products, manufactured in a set of L product lines during a planning horizon of T periods. The aim of the company is to maximize the global net profit balancing the sales revenue and operational costs subject to the plant capacity over the planning horizon T. The indexes, sets, constants, and variables are listed below, followed by the model formulation.

Objective

z: total profit [$].

Sets

I: set of products i.

L: set of product lines l.

T: set of time periods t.

Variables

Inv_{it}: inventory units of product i in period t [units].

B_{it}: unfulfilled units of product i in period t [units].
Z_{ilt}: binary variable that takes value of 1 if a set-up is made for product i on production line l in period t [0,1].
Mp_{ilt}: manufactured units of product i on production line l in period t [units].
S_{it}: sold units of product i in period t [units].

Constants

M: A big number.
Cs_{il}: set-up cost of product i manufactured on production line l [$].
Cp_{il}: production cost of product i manufactured on production line l [$].
Ch_i: holding cost of product i on inventory [$].
Cb_i: cost of unfulfilled product i [$].
Ts_{il}: set-up time of product i manufactured on production line l [time units].
Tp_{il}: time required to produce product i on production line l [time units].
Q_l: maximum capacity of the production line l [time units].
β_{it}: availability of the production line l in period t [0-1].
d_{it}: demand forecast for product i in period t [units].
P_{it}: sale price of product i in period t [$].
$Inv0_i$: initial inventory units of product i [units].
SS_{it}: safety stock units of product i in period t [units].

Objective Function

$$Max\ z = \sum_{i=1}^{I}\sum_{t=1}^{T} P_{it}S_{it} - \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} Cs_{il}Z_{ilt} - \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} Cp_{il}Mp_{ilt} - \sum_{i=1}^{I}\sum_{t=1}^{T} Ch_i Inv_{it} - \sum_{i=1}^{I}\sum_{t=1}^{T} Cb_i B_{it} \quad (1)$$

Subject to

$$\sum_{i=1}^{I}(Ts_{il}Z_{ilt} + Tp_{il}Mp_{ilt}) \leq \beta_{lt}Q_l \qquad \forall l,t \qquad (2)$$

$$Mp_{ilt} \leq MZ_{ilt} \qquad \forall l,t \qquad (3)$$

$$Inv_{it} = Inv_{it-1} + \sum_{l=1}^{L} Mp_{ilt} - S_{it} \qquad \forall i, t = 2,\dots,T \qquad (4)$$

$$Inv_{i1} = Inv0_i + \sum_{l=1}^{L} Mp_{i1} - S_{i1} \qquad \forall i,t \qquad (5)$$

$$S_{it} = d_{it} - B_{it} \qquad \forall i,t \qquad (6)$$

$$Inv_{it} \geq SS_{it} \qquad \forall i,t \qquad (7)$$

$$S_{it}, Mp_{ilt}, Inv_{it}, B_{it} \geq 0; \qquad \forall i, l, t \qquad (8)$$

$$Z_{ilt} = \{0, 1\} \qquad \forall i, l, t \qquad (9)$$

In the objective function (1), the first expression represents the total net profit. The second and third term describe the setup and production costs. The last terms represents the inventory and stockout costs. Constraint (2) is the capacity constraint in time units for each production line. Constraint (3) guarantees that there can be production in a period and production line, only if there is a setup. Constraints (4) and (5) enforce inventory balance. Constraint (6) defines the amount of products *i* to be sold according to the demand forecast and the unfulfilled units for each period of time *t* and demand scenario k. Constraint (7) sets the minimum safety stock for each product *i*, each period *t*. Constraints (8) and (9) are non-negativity constraint for all variables, specifying Z_{ilt} as binary.

3.2 The Rolling Horizon method

For this study, we define *H* as the number of periods for which we wish to create production plans. The planning horizon each time the model is run is of *T* periods, $T < H$. Parameter *R* is introduced to help describe the general rolling horizon strategy. *R* is a horizon ($R<T<H$) in which production plan is fixed and the real demand can be observed and used to update forecast, adjusting the plan over a planning horizon of *T* periods. The steps of the algorithm are further described:

1. Make the forecast for the demand in $t=1...T$ with its respective measures of error and deviation. Run the model to get the production plan Mp_{ilt}. Set the current period as $c = 1$.
2. For $t=c...R$, fix the resulting production plan and take the values of actual demand in this horizon. Save these values as parameters Mp_{ilt} and d_{it} respectively in the MILP model. Run the model with this update and get the values of Inv_{it} and B_{it}.
3. For $t = R + 1, \dots, R + T$, update the forecast and run the model in the same way as step 1 recognizing the current period is updated by *R* periods to the current time, and considering the value of $Inv_{iR} = Inv0_i$ in this horizon.
4. If $c < H$, update $H=H-R$ and return to step 2; else, stop.

4 The experimental design

The experimental design was performed to test the impact of specific factors, both forecast error and production flexibility on total profits of the company. We propose a factorial design 2^k. For the statistical analysis, *Minitab 18* was used in all combinations generated of three factors that were varied in two levels, high and low. In total, we will consider 2^3 instances* 5 replicates = 40 aleatory experiments.

4.1 Instance Generation

The bias of the forecast demand error is considered in order to evaluate the inaccuracy of the method employed by the company to forecast the demand. With respect to the flexibility of the production system, we consider the level of safety stocks. The length of the frozen horizon is also included in the experiment. The value of Tp_{il} is equal to 1 second per piece and Ts_{il} is 25 minutes. Given that the company does not have capacity limitations, we assume that capacity is high enough to produce all the units required by the company. Table 2 presents the rest of the parameters and their values for the high and low level of the experiments. The values were defined according to the characteristics of the case study under consideration. The bias factor is interpreted as the percentage by which the real demand is underestimated. Thus, a value of 60% indicates that the forecast is on average only 40% of the real demand.

Table 2. Parameters to evaluate in the factorial experimental design.

Parameter	Nomenclature	High Level	Low Level
SS	Safety stock service level	95%	85%
bias	Absolute value of bias *(underestimated)*	60%	10%
R	Number of periods in the frozen horizon	6	1

To generate the instances, a data set of real demand faced by the company corresponding to the periods from year 2016 was used for experimental purpose. The forecasts were prepared with the specified bias and Root-Mean-Square Error (RMSE) as representative for the company's historical forecast error.

4.2 Numerical results and discussion

The proposed MILP was implemented in AMPL TeamEAT Version 20120911 (MS VC++ 6.0, 32-bit) with Gurobi 5.0.1 as the solver. The rolling horizon procedure was automated with Python 3.6, using the *amplpy* library for interacting with AMPL. Likewise, *pandas* and *xlrd* libraries were used to read instances files and write files with the results of the experiments. To solve the test instances, an Intel Core (TM) i3-6006U CPU @ 2.00 GHz 1.99 GHz computer, with 8gb RAM was used. The runtime for 40 instances was 3 hours, 1 minute and 20 seconds. The overall results of the experiments are summarized in Table 3. The minimum, mean and maximum values obtained for each of the variables is shown, as well as the minimum, mean and maximum computational times for the solved instances. Tables 4 through 9 present the results by parameter level.

Table 3. Global results after implementing the solution method with Python.

Value	Mp	S	B	Inv	Profit(z)	Computational time

Min	558	558	155	0	$48376.00	01:12 min
Mean	939	905	533	44	$99909.25	04:32 min
Max	1443	1284	880	207	$160806.00	05:59 min

Table 4. Performance of safety stock level on variables and total profit

SS (1-α)	Value	Mp	S	B	Inv	Profit(z)
High level = 95%	Min	559	559	155	0	$48415.00
	Mean	965	913	526	65	$99780.25
	Max	1443	1284	880	207	$160806.00
Low level = 85%	Min	558	558	155	0	$48376.00
	Mean	917	903	535	31	$100972.36
	Max	1251	1241	880	56	$153985.00

Table 5. Performance of bias on variables and total profit

bias	Value	Mp	S	B	Inv	Profit(z)
High level = 60%	Min	558	558	843	0	$48376.00
	Mean	571	571	867	0	$50423.50
	Max	595	595	880	0	$54109.00
Low level = 10%	Min	1250	1195	155	38	$139106.00
	Mean	1307	1239	200	89	$149395.00
	Max	1443	1284	880	207	$160806.00

Table 6. Performance number of periods in frozen horizon on variables and total profit

R	Value	Mp	S	B	Inv	Profit(z)
High level = 6	Min	558	558	155	0	$48376.00
	Mean	913	910	528	23	$102895.50
	Max	1284	1284	880	54	$160806.00
Low level = 1	Min	574	574	203	0	$50794.00
	Mean	966	900	539	66	$96923.00
	Max	1443	1236	865	207	$143683.00

As can be observed in previous tables, the parameter related to the bias has an important effect on profits. For the rest of the parameters, the profits do not present a significant variation in the results obtained by each level. However, the frozen horizon R has an impact on the values of inventory, with a higher mean and maximum value when we consider the low level of R=1.

In addition to the results shown in the above tables, to verify the significance of the factors studied on the variables of interest, a multivariate regression analysis was performed. For this, Minitab 18 version was used. The analysis considered the step-by-step method to eliminate non-significant terms. The only coefficient that resulted significant for total profit as an individual factor was the bias. The rest of the parameters only have an impact interacting directly with bias, that is, their behavior depends on the level of bias: the safety stock level *SS (1-α)* and the number of periods of frozen horizon R. Tp_{il} and Ts_{il} depend strictly on previous interaction to be significant. An R-square adjusted value of 84.8% was obtained. Table 7 summarizes these results.

Table 7. Significance of the coefficients.

Term	Coefficient	Standard Error Coefficient	T-value	P-value	Variance Inflation Factor (VIF)
Constant	126505	2098	60.31	0	
bias	-103504	5552	-18.64	0	2.19
SS*bias	-179520	74970	-2.39	0.018	1
R*bias	-21675	2374	-9.13	0	1.19

Considering the factors and interactions that resulted more significant, we present a comparative analysis of them with respect to profits: (i) bias; (ii) Interaction of bias and *R*; and (iii) Interaction of bias and safety stocks.

(i) Comparative analysis of bias with respect to profits

Fig.1 presents the behavior of high and low level of bias on profits during experimentation. We can observe a decrease on profits when bias is higher, so the lower the value of this, the higher the benefits, which lead us to conclude that profits are highly influenced by the bias.

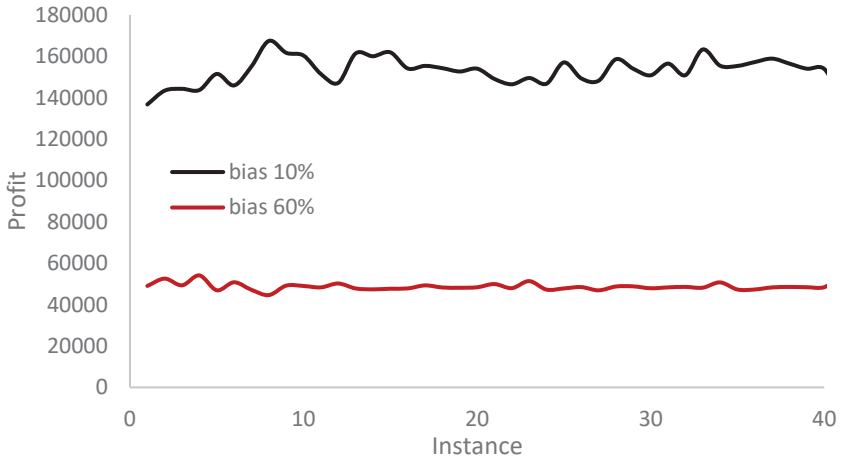

Fig.1. Comparative analysis of the levels of bias with respect to total profit

(ii) Comparative analysis of the interaction of bias and R with respect to profits

Fig. 2 illustrates the behavior of bias and *R* with respect profits. As we can observe, when the bias has the biggest value (60%), the profits are low, even for a shorter length of the frozen period *R* (*R=1*), but these short-frozen period tends to raise the profits a little by fast reaction. On the other hand, when the bias is small (10%), more stable and better profits are achieved when the length of the frozen period *R* is higher (*R=6*).

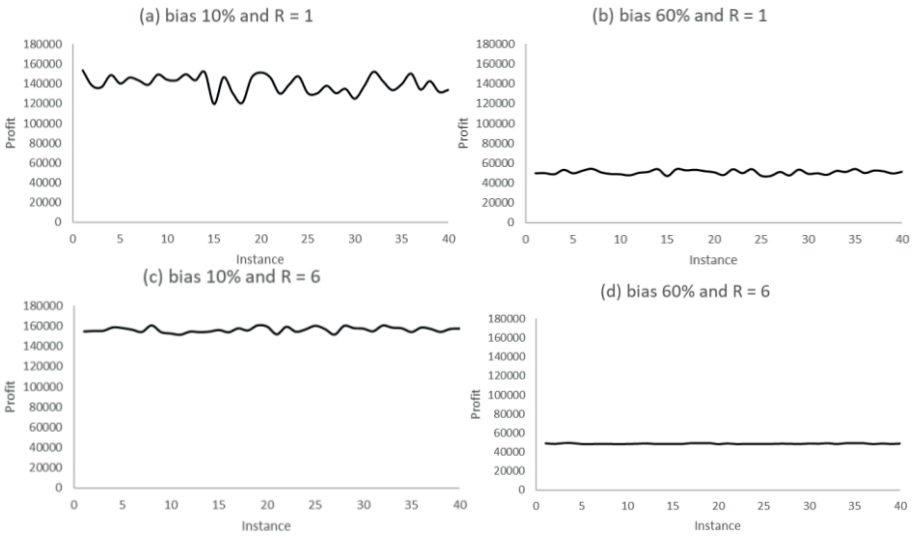

Fig.2. Analysis of the interaction of bias and the frozen period *R* with respect to total profits.

(iii) Interaction bias and Safety Stocks on profits comparative analysis

Fig. 3 presents the corresponding graphs to compare the bias and safety stock with respect to profits. As we can observe in the figure, for the same safety stock level, the level of bias has an important effect on total profits, being significantly higher when the bias is small (10%). The same conclusions can be derived when considering a higher safety stock level (95%), significant differences on the profits are achieved depending on the level of bias.

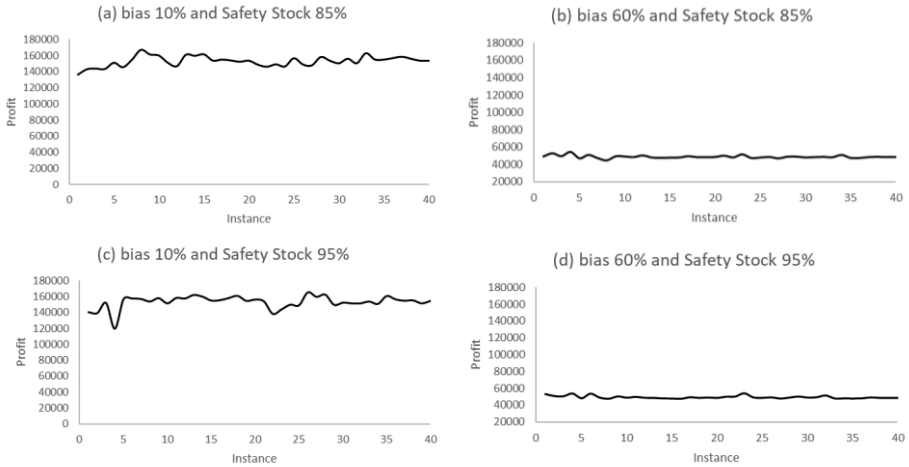

Fig.3. Analysis of the interaction of bias and safety stocks with respect to total profits

5 Conclusions and recommendations for future research

In this paper, we have proposed a Mixed-Integer Linear Programming (MILP) optimization planning model, motivated by a case study company that produces snacks in Monterrey, Mexico. To solve the model, a rolling horizon scheme is considered in order to resemble current practices of the production managers of the company, that determine their aggregated plans for a medium term planning horizon, and adjust them according to the demand faced. The proposed framework has been implemented in Python and AMPL.

Numerical experiments were performed, for which a set of instances were generated. Values of the parameters were defined to resemble the operations of the company. The experiments incorporated the forecast bias as a factor to be considered, to evaluate the impact that this has on profits and the other variables of the model (production amount, inventories, etc.). We also performed a statistical analysis to determine the factors that are most significant on the profits. Results show that the bias is the most significant factor affecting profits, and the other variables. The rest of the factors are not significant. Only the interaction of the bias and the frozen period R, and the interaction of bias and safety stock.

For future research we propose to extend this work in two ways. First, consider a stochastic version of the problem that can consider different demand scenarios. And the second aspect is to incorporate a recourse action during the frozen period R, considering the situation in which the company is more flexible and can adjust their production plans according to demand changes or changes in the customer´s orders.

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Alistamiento de pedidos en un almacén de comercio electrónico: una revisión

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Resumen.
Propósito- obtener una perspectiva acerca de los problemas de enrutamiento de un recolector y alistamiento de pedidos en un almacén.
Diseño / enfoque- se efectúa una revisión sistemática de la literatura para identificar modelos matemáticos que abordan las operaciones de preparación de pedidos; haciendo especial énfasis en la forma de almacenamiento y su impacto en dicha labor.
Hallazgos- la revisión de la literatura reveló que gran parte de las publicaciones en revistas científicas han desarrollado el problema de enrutamiento en un sistema de almacenamiento tradicional, han sido pocos los artículos que abordan este problema en un sistema de almacenamiento disperso, por lo que es un campo con muchas oportunidades de investigación.
Limitaciones / implicaciones de la investigación- se describe una agenda orientada de investigación, en la cual se analiza profundamente las estrategias propuestas para la optimización de las operaciones de preparación de pedidos.
Implicaciones prácticas: se muestra un tema de investigación bastante novedoso, por tanto, se presenta como una propuesta a considerar para futuras investigaciones.
Originalidad / valor- esta revisión presenta una línea de tiempo de los modelos que se han propuesto por diversos autores a lo largo de los años, haciendo un paralelo en el enfoque se le ha dado a la solución del problema de enrutamiento de un recolector en almacenes tradicionales y con almacenamiento disperso, una forma de almacenamiento que ha tomado fuerza y ha sido poco documentada.
Palabras clase: Logística, Revisión de literatura, Almacenamiento tradicional, Almacenamiento disperso, Comercio electrónico.
Tipo de papel: Revisión de literatura.

1 Introducción

La industria está atravesando un proceso de cambios vertiginosos por causa de los constantes avances en las tecnologías de la información y la comunicación, siendo el internet el medio de comunicación más utilizado actualmente y partiendo de la necesidad de las empresas por facilitar a los clientes los procesos de compra, surge con gran fuerza la era del comercio electrónico; una alternativa que permite a los usuarios acceder, seleccionar y pagar los productos en cualquier momento y lugar del mundo (Weidinger, 2018). El comercio electrónico (E-commerce) es un proceso de compra, venta, distribución, mercadeo y/o suministro de información de bienes o servicios a través de Internet (Alejandro López Ruiz, 2018) , este comercio utiliza las variadas formas que existen de relacionarse entre empresas y consumidores, una de las más frecuentes es la de tipo empresa-consumidor (B2C) utilizada por los minoristas de comercio electrónico que atienden la demanda del cliente final; el desarrollo de E-commerce tipo B2C ha presentado nuevos desafíos para las empresas, uno de ellos es el proceso logístico de preparación de pedidos en los almacenes, ya que es complejo por sus ajustados tiempos de entrega y por la gran variedad de pedidos en pequeñas cantidades (Roxana Silva, 2009).

Al presente, uno de los retos más grandes que enfrenta el comercio electrónico, es la preparación de pedidos, que consiste en extraer y organizar los productos demandados por los clientes. Se conoce como la actividad más importante en los almacenes, ya que, representa hasta el 60% de todas las actividades laborales en el mismo y, para un almacén típico, el costo de la preparación de pedidos se estima en hasta el 55% del gasto operativo total del almacén (Tompkins et al., 2003).

El almacenamiento disperso (también llamado estanterías mixtas) surge como una solución alternativa para este desafío logístico que afronta el E-commerce B2C, en donde las cargas unitarias se dividen en artículos individuales que se distribuyen por todo el almacén, lo que lleva a múltiples posiciones de almacenamiento por unidad de mantenimiento de existencia (Weidinger, 2018). Partiendo de esto, los productos son organizados de forma aleatoria en diferentes estantes, de modo que el selector tiene la oportunidad de encontrar los artículos demandados en un menor tiempo debido a que aumenta la probabilidad de encontrarlos en distancias menores (Weidinger, Boysen y Schneider, 2019).

Teniendo en cuenta que el almacenamiento disperso supone una alternativa viable para optimizar los tiempos de preparación de pedidos para E-commerce B2C, En esta revisión se abordaran dos aspectos: el primero, la transición y las ventajas que tiene el almacenamiento disperso en los almacenes de comercio electrónico , con el objetivo de establecer una nueva perspectiva respecto a los sistemas de almacenaje tradicional; segundo, enfoques de solución al problema de enrutamiento de un recolector (Single Picker Routing Problem , SPRP) en el que se busca optimizar la ruta que recorre el selector en el proceso de picking, también conocido como preparación de pedidos.

En la literatura se encuentran varias revisiones acerca del enrutamiento del recolector de pedidos en los almacenes tal como en Masae, M., Glock, C., & Grosse, E. (2019). Es por esto que el propósito de este estudio es sintetizar toda la información acerca del proceso de picking en almacenes de comercio electrónico partiendo de las diferencias existentes entre almacenamiento tradicional y almacenamiento disperso o también conocido como estanterías mixtas.

2 Almacenamiento tradicional y almacenamiento disperso.

Al caracterizar los almacenes de recolectores a partes, en la literatura actual se distingue entre almacenamiento dedicado y compartido, Para la estrategia de almacenamiento dedicada o tradicional, cada unidad de mantenimiento de existencias (SKU) tiene una posición de almacenamiento fija, mientras que en el almacenamiento compartido o disperso las SKU entrantes se asignan a cualquier posición de almacenamiento adecuada disponible (Weidinger, 2018).

La principal intención del almacenamiento disperso es que, con las unidades esparcidas por todo el almacén, las distancias promedio desde cualquier lugar del almacén hacia la unidad más cercana de cada SKU se reducen considerablemente, esto aumenta la probabilidad de que un SKU demandado esté cerca (Boysen, Koster, Weidinger, 2018). Además, los almacenes de estantes mixtos suelen tener varios puntos de acceso (depósitos) donde los pedidos completados se entregan al sistema de transporte central, de esta manera, la improductividad de los recolectores disminuye considerablemente y se pueden cumplir mejor los horarios de entrega ajustados (Boysen, Koster, Weidinger, 2018).

3 Estructura del trabajo

Este documento es una revisión de literatura sobre los problemas de enrutamiento de un recolector y alistamiento de pedidos en un almacén. Primero, se presenta la metodología utilizada para llevar a cabo la investigación. En la (sección 2) se encuentra la información obtenida en la revisión, mediante dos líneas de tiempo, la primera muestra los métodos de solución propuestos antes del almacenamiento disperso y la segunda presenta los métodos propuestos después del almacenamiento disperso. En la (sección 3) se muestra cómo se le ha dado solución al problema de Enrutamiento de un recolector. Finalmente, las conclusiones son presentadas en la (sección 4).

4 Metodología

Para el desarrollo de la revisión de literatura acerca del problema de enrutamiento de un recolector (Single Picker Routing Problem, SPRP) en los almacenes de comercio electrónico, se realizaron los siguientes pasos:

Primero, se identificó el objetivo de la investigación, para este tipo de revisión se hizo uso de las bases de datos conocidas como Scopus, Web of Science, ScienceDirect. En primera instancia se buscaron artículos relacionados con los sistemas de almacenamiento y los problemas que se encontraban dentro de estos, se identificó que el problema principal del que se quería realizar la revisión era el conocido como SPRP, también llamado single picker routing problema enfocado en almacenes de comercio electrónico.

En segundo lugar, se identificaron las dos bases de datos principales de las que se iba a extraer la información, estas bases de datos son Scopus y Web of Science; seguido de esto se establecieron dos ecuaciones de búsqueda con las que se iban a refinar los resultados de la revisión de literatura.

Tercero, se encontraron los resultados dados por las bases de datos, además se realizó un análisis tipo bola de nieve de citas en los artículos más relevantes y se analizaron mediante el software libre VOSviewer, una herramienta que permite construir y visualizar redes bibliométricas, realiza también redes de co-ocurrencia, co-autoria, acoplamiento bibliométrico; a partir de técnicas de minería, mapeo y análisis de clusters.

Para Scopus la búsqueda incluyó las palabras clave “mixed shelves”, “picker”, “routing”, “tabu search”, “e commerce”, obteniendo 36 documentos. Para el análisis bibliométrico realizado en la base de datos Web of Science, se obtuvieron 60 artículos en idioma inglés, que fueron alcanzados con la ecuación de búsqueda: mixed shelves *and* routing *and* e commerce *or* tabu search *and* warehouse.

En cuarto lugar, se llevó a cabo una síntesis de la información y un análisis detallado acerca del tema seleccionado para la revisión de literatura; mediante este paso se desarrolló un análisis preliminar de literatura en donde se destacan los trabajos de diferentes autores relacionados con el problema SPRP para almacenes de comercio electrónico y esta revisión se divide en dos partes, la primera hace referencia a las publicaciones que trataron el tema teniendo en cuenta el almacenamiento tradicional y la segunda parte, hace referencia a las publicaciones que contemplaron el almacenamiento disperso, también conocido como estanterías mixtas.

Finalmente teniendo toda la información sintetizada se realiza un segundo análisis de publicaciones relacionados única y exclusivamente con el problema SPRP para almacenes de comercio electrónico con almacenamiento disperso, esto con el fin de tener un conocimiento más amplio acerca del tema.

5 Análisis

Todas las empresas que se encuentran relacionadas con el comercio electrónico, presentan grandes ventajas tales como, la facilidad de promocionar sus productos mediante plataformas virtuales, ofrecer a los clientes diferentes medios en los que se pueden efectuar las compras, entre otras. Por otro lado, se encuentran con actividades laboriosas, como lo es la preparación de pedidos dentro de los procesos de almacenamiento, ya que esta requiere más tiempo y por lo tanto más trabajo. Algunos autores estimaron que representa hasta el 55% de los costos operativos totales del almacén y que se vuelve más complejo en almacenes de comercio electrónico debido a las grandes cantidades de pedidos (Tompkins, White, Bozer & Tanchoco, 2010).

A lo largo del tiempo, se han propuesto diferentes modelos matemáticos con los que se pretende ayudar a optimizar las operaciones de preparación de pedidos. Tres de los problemas que se tienen en cuenta en este tema son, la asignación de artículos a las diferentes ubicaciones de

almacenamiento (Grosee, Glock & Neumann, 2017), el procesamiento por lotes de pedidos y el enrutamiento del preparador de pedidos a través del almacén (Van Gils, Ramaekers, Caris & Koster, 2018). Para la solución de estos problemas se han propuesto tres métodos diferentes de solución.

1. Los algoritmos exactos, por medio de estos se llega a una solución óptima. Algunos ejemplos en donde se ha utilizado este método como solución son, De Koster y Van der Poort (1998), y Roodbergen y De Koster (2001a, b).
2. Las heurísticas, se definen como algoritmos dependientes de problemas creados con sus especificaciones (Sörensen, 2015). Algunos ejemplos son, heurística del punto medio, forma de S, retorno, combinada; se encuentran explicados en Roodbergen y De Koster (2001).
3. Las metaheurísticas, se definen como algoritmos independientes de problemas de alto nivel. Algunos ejemplos son optimización de colonias de hormigas (OCH), algoritmo genético (AG), búsqueda Tabú (BT) en Daniels, Rummel & Schantz, (1998).

El problema del enrutador de pedidos en un almacén se relaciona al problema clásico del vendedor ambulante (TSP) así como lo exponen Ratliff y Rosenthal, 1983. En esta investigación, los autores abordan el problema en un almacén rectangular que contiene cruces solo en los extremos de los pasillos. Años más tarde, Kashi y Dirk, 1997; consideran una generalización del problema del vendedor ambulante (TSP) llamado problema del comprador viajero (TPP), en el que se busca comprar los productos visitando subconjuntos de mercados en un recorrido de manera que los costos totales de viaje y compra sean minimizados (Ravi and Salman,1999).Y como método de solución para resolver el problema en relación con la ubicación de la planta, los autores proponen un algoritmo de ramificación y acotamiento, también conocido como Branch & Bound. Mediante esta investigación se llega a la conclusión que los problemas de tamaño de hasta 25 ciudades y 100 productos se puede resolver mediante el algoritmo, obteniendo resultados en un tiempo de cálculo razonable; también se demuestra que el problema del comprador viajero tiene aplicaciones en las áreas de programación, almacenamiento y enrutamiento (Kashi, Dirk,1997) siendo de gran importancia para futuras investigaciones.

Rubrico, Ota, Higashi y Tamura, 2008; Resuelven el problema de programación mediante la metaheurística Búsqueda Tabú, se busca que la demanda sea transferida entre los agentes para equilibrar la carga y de

esta forma sea más eficiente el proceso de picking dentro de la gestión del almacén. Posterior a esto, Henn y Wascher, 2012. Lo que se pretende es combinar un conjunto de pedidos para luego agruparlos y de esta manera se minimice la duración total de todos los recorridos de recolección para los artículos solicitados; convirtiéndose en un problema de procesamiento por lotes de pedidos, los autores lo resuelven mediante dos enfoques basados en el principio de búsqueda tabú, demostrando que los métodos propuestos proporcionan soluciones que permiten la eficiencia de la operación en los almacenes de distribución.

Tiempo después, Liu, Li y Liu, 2017; añaden al problema de enrutamiento de vehículos la variante de la capacidad y con tiempo de pedido disponible (CVRPOAT), se analiza dicho problema ya que se encuentra inmerso en las operaciones de la industria de comercio electrónico. Se busca minimizar la suma de los tiempos de finalización del vehículo; se presenta un algoritmo de búsqueda tabú para abordar el tema y se compara con un algoritmo genético, los resultados indican que el algoritmo de búsqueda tabú es superior al algoritmo genético para tratar el problema mencionado.

Otro aspecto importante a tener en cuenta en la industria de comercio electrónico es la preparación de pedidos, proceso mediante el cual se recuperan artículos de sus ubicaciones de almacenamiento para satisfacer los pedidos de los clientes. Zulj, Glock, Grosse y Schneider, 2018; parten de la necesidad de generar un ahorro considerable de tiempo y costos en el proceso considerado como el más laborioso en el almacenamiento, y buscan una solución para un almacén en el que la asignación de almacenamiento está determinada por el peso de los artículos. Los autores utilizan el algoritmo basado en graficos propuesto por Ratlif y Rosenthal (1983) y proponen una estrategia de que busca brindar estrategias para el proceso de asignación mencionado.

Para el problema de asignación de pedidos, el procesamiento por lotes de pedido y los problemas de enrutamiento de recolectores en los almacenes de recolección de olas, Ardjmand, Shaker i, Singh y Bajgiran, 2018; presentan un modelo matemático que se resuelve mediante un algoritmo exacto de descomposición lagrangiana combinado con un algoritmo de optimización de enjambre de partículas. En los problemas a gran escala se utiliza recocido simulado paralelo hibrido y optimización de colonias de hormigas. Los autores en su investigación, mediante experimentos numéricos muestran que el aumento de la cantidad de recolecto-

res y la capacidad de recolección presenta un mayor impacto en la reducción de la producción improvisada cuando existe proporcionalidad entre los pedidos y la cantidad de recolectores.

En el año siguiente, se realiza una investigación teniendo en cuenta los avances tecnológicos en la robótica móvil, Lee, H.-Y., Murray y C.C, 2019; exploran un enfoque diferente al habitual para la preparación de pedidos de un almacén. En dicha investigación se consideran dos tipos de robots que realizan los procesos de recolección de artículos y de entrega a la estación de empaque. Los autores desarrollan una formulación de programación lineal entera mixta, mediante la cual llegan a las conclusiones, aumentar el número de pasillos transversales disminuye el rendimiento del sistema; las estaciones de empaque ubicadas en el centro mejoran el rendimiento del sistema; y la distancia promedio desde cada ubicación de recolección hasta la estación de empaque y la distancia promedio entre ubicaciones de recolección son métricas efectivas para identificar cambios específicos en la flota (Lee, H.-Y., Murray, C.C.,2019).

En todas las investigaciones se ha determinado que el diseño del almacén es fundamental para la optimización de las operaciones de preparación de pedidos. Yener y Yazgan, 2019; investigan la efectividad del diseño de almacenes para determinar el tiempo promedio del proceso de preparación de pedidos y la distancia recorrida mediante una técnica de minería de datos. En el mismo año, Boysen, Koster y Weidinger, 2019; presentan un ensayo en el que se exponen todos los tipos de sistemas de almacenamiento que han optado los minoristas de comercio electrónico, desde los tradicionales hasta la adaptación de las estanterías mixtas, también conocido como almacenamiento disperso.

Al abordar la temática de almacenamiento disperso, es necesario mencionar que han sido pocos los documentos publicados sobre el tema; según la revisión sistemática de la literatura publicada en Masae, Glock, & Grosse, (2019) en una muestra central de 54 documentos tan solo 4 han desarrollado el problema de enrutamiento en un sistema de almacenamiento disperso, lo cual permite evidenciar un campo de oportunidades para desarrollar algoritmos de enrutamiento para esta área.

En Singh & Oudheusden, (1997) por primera vez se estudia un almacén con almacenamiento disperso. En este artículo no se tuvo en cuenta el diseño particular del almacén, sino que se planteó el objetivo de encontrar un recorrido que minimizara la suma de los gastos de la ruta de viaje y la compra para el problema del comprador viajero (TPP). El tema

de almacenamiento disperso es introducido en el artículo cuando se proponen aplicaciones potenciales de la estructura del problema del agente viajero y se enuncia que para una situación en la que un artículo se almacena en un área de ubicación única del almacén, el problema ha sido reconocido como una variante del problema TPS, pero cuando un artículo se almacena en más de un área, el problema tiene la estructura de un TPP siendo ésta bastante compleja de resolver, por lo que para dar una solución se consideró un algoritmo de ramificación y acotamiento que funciona para cualquier tipo de matriz que considere las distancias de viaje de una ubicación de almacenamiento a otra (Masae, Glock, & Grosse, 2019)

Con el seguimiento computacional de los inventarios, las piezas ahora se pueden almacenar en múltiples ubicaciones. En Daniels, Rummel, & Schantz, (1998) se estudia la preparación de pedidos para una secuencia en la que se visita una sola vez cada ubicación del almacén donde las piezas se almacenan en múltiples ubicaciones, simplificando la reposición de inventario y eliminando la necesidad de reservar espacio para cada artículo. Se contempla el conjunto de ubicaciones en las que se almacena cada pieza y la cantidad de stock en cada una de ellas, siendo un problema combinatorio de asignación y secuenciación. Para su solución se muestra un procedimiento basado en la búsqueda tabú y una prueba de dureza NP para matrices de distancia .

El auge de la venta de minoristas en línea de empresa a consumidor, ha hecho que surja la necesidad de adaptar las estrategias de almacenamiento a las necesidades particulares que se derivan de este mercado. Las nuevas estrategias deben hacer frente a múltiples desafíos tales como pedidos pequeños y tiempos de entrega críticos. Bajo esta circunstancia, emplear una estrategia de almacenamiento tradicional, con solo una o unas pocas posiciones de almacenamiento por SKU, daría como resultado largos recorridos de recolección. Por el contrario, una nueva estrategia emergente adaptada a las necesidades de los minoristas en línea, esta estrategia es conocida como almacenamiento disperso (Weidinger, 2018).

En Weidinger 2018, se investiga el problema de enrutamiento del recolector en un almacén de almacenamiento disperso rectangular, donde se pueden encontrar artículos del mismo SKU en diferentes posiciones de almacenamiento; lo que se busca es el recorrido más corto que permita satisfacer la demanda. El problema consiste en una selección y enrutamiento interrelacionados entre sí. Se proporciona una prueba de dureza

NP y se presentan tres heurísticas de enrutamiento utilizando reglas de selección de ubicación de almacenamiento que calculan los valores de prioridad para los artículos solicitados, que influyen en la secuencia de selección de los artículos solicitados en un pedido.

En Weidinger, Boysen & Schneider, (2019) se extendió el problema ya que se contaba con los depósitos ubicados en los extremos trasero y delantero de cada pasillo, de esta forma los puntos de inicio y finalización de los recorridos podían ser cualquiera de estos dos. Para dar solución a esto se adaptó el enfoque del vecino más cercano con el que se buscaba encontrar una primera solución factible para el ruteo del selector con estanterías mixtas (MSPR), cabe destacar que en este documento se resalta que el almacenamiento disperso es adecuado cuando se tienen pedidos de pequeño tamaño que requieren pocos artículos por línea de pedido, cuando se produce un pedido ocasional más grande con múltiples artículos, el stock en un solo estante puede no ser suficiente, y el recolector tiene que visitar múltiples posiciones de almacenamiento para reunir suficientes artículos. Por lo tanto, los pedidos de gran tamaño aumentan el esfuerzo de recolección bajo el almacenamiento de estanterías mixtas (Weidinger, Boysen, & Schneider, 2019).

En Yang, Chao & Guo (2020) se abordó la investigación desde la formulación de problemas de optimización de selección de lotes de pedidos para tres sistemas de almacenamiento típicos, la principal contribución de este documento es explorar exhaustivamente los problemas de optimización de preparación de lotes de pedidos mediante la formulación de modelos y desarrollos de algoritmos desde la perspectiva de diferentes escenarios de almacenamiento (Yang, Chao, & Guo, 2020). Los autores usaron cuatro tipos de algoritmos para resolver el problema de procesamiento por lotes de pedidos para los diferentes sistemas de almacenamiento, dichos algoritmos fueron: El algoritmo de distancia de intervalo de ubicación en donde se calcula la distancia entre ubicaciones de almacenamiento, el algoritmo de selección de ubicación con el que se elige la ubicación de selección de varias ubicaciones que almacenan la SKU idéntica, el algoritmo de enrutamiento decide la ruta de un recolector para visitar los lugares seleccionados en un viaje, el algoritmo de procesamiento por lotes de pedidos agrupa los pedidos en lotes.

Cabe destacar que en los resultados de esta investigación se evidencia que el rendimiento de las combinaciones de algoritmos propuestos es satisfactorio para resolver problemas con diferentes tamaños, tanto en calidad de la solución como en eficiencia del cálculo.

6 Enfoque a SPRP

El problema de enrutamiento de un solo recolector trata con la determinación de la secuencia de acuerdo con las ubicaciones de los artículos que se deben visitar en un almacén de distribución y la identificación de las rutas correspondientes que deben recorrer los operadores humanos (recolectores de pedidos) para recolectar conjunto de artículos solicitados por clientes internos o externos (Scholz, Henn, Stuhlmann, & Wäscher, 2016). El problema de enrutamiento de un solo selector (SPRP) representa un caso especial del clásico problema del vendedor ambulante (TSP) y, por lo tanto, también se puede modelar como un TSP (Scholz, Henn, Stuhlmann, & Wäscher, 2016).

En Ratliff y Rosenthal (1983) se define al problema de preparación de pedidos como uno de los más importantes a tener en cuenta en el proceso de almacenamiento, dicho problema se reconoce como una variante del conocido y complejo problema del vendedor ambulante.

En Daniels, Rummel , & Schantz (1998) se define que la preparación de pedidos en entornos de almacén convencionales implica determinar una secuencia en la que hay que visitar las ubicaciones únicas donde se almacena cada parte del pedido, y por lo tanto a menudo se modela como un problema de vendedor ambulante. En esta investigación se formuló un modelo para determinar simultáneamente la asignación y las decisiones de secuencia, y se comparó con modelos anteriores para la preparación de pedidos. Se discute la complejidad del problema de preparación de pedidos y se establece un límite superior en el número de asignaciones factibles, se presentan y prueban experimentalmente varias extensiones de la heurística de TSP a la nueva configuración del problema y un algoritmo de búsqueda tabú.

En Scholz, Henn, Stuhlmann, & Wäscher (2016) tratan una aplicación del TSP que surge en la gestión del almacén de distribución en cuanto a su función principal, la preparación de pedidos. En este documento se presenta la primera formulación matemática para el SPRP que tiene en cuenta las propiedades específicas de las soluciones óptimas de este problema. En particular, se demuestra que el tamaño de la formulación es independiente del número de ubicaciones donde se deben elegir los artículos, mediante extensos experimentos numéricos se demuestra que la formulación propuesta para el SPRP es superior a las formulaciones estándar de TSP y Steiner TSP. Se considera el problema de enrutamiento de un solo selector en un diseño de bloque único que representa un caso

especial del problema del vendedor ambulante, centrándose en el SPRP en diseños de bloque único, pero también se demostró cómo varias situaciones relevantes como el diseño de bloques múltiples, depósito descentralizado se integran a la formulación propuesta (Scholz, Henn, Stuhlmann, & Wäscher, 2016).

En Schneider & Goeke (2018) se establece que el problema estándar de enrutamiento de un solo recolector (SPRP) busca el recorrido de costo mínimo para recolectar un conjunto de artículos dados en un almacén rectangular de un solo bloque con pasillos de picking paralelos y una política de almacenamiento dedicada, es decir, cada SKU solo está disponible desde una ubicación de almacenamiento en el almacén (Schneider & Goeke, 2018). Se presenta una formulación compacta que renuncia a las restricciones clásicas de eliminación de subtour explotando directamente dos de las propiedades de un recorrido de picking óptimo utilizado en el algoritmo de programación dinámica de Ratliff y Rosenthal (1983) y se extiende la formulación de tres entornos importantes que prevalecen en los modernos almacenes de comercio electrónico: almacenamiento disperso, desacoplamiento del recogedor y el carro, y múltiples depósitos finales.

En Weidinger (2018) se investiga el problema de enrutamiento del selector en un almacén con un sistema de almacenamiento disperso rectangular, se identifica como un problema combinado de selección y enrutamiento. En esta investigación se opta por analizar este tipo de almacenamiento ya que es considerada una nueva estrategia emergente adaptada a las necesidades de los minoristas en línea. Para dar solución al problema propone tres enfoques con el fin de calcular los valores de prioridad P para una determinada posición, dichos enfoques son, Single position, MinMax y MinMin. El objetivo es encontrar el recorrido de selección más corto, el problema se conforma en dos partes, una primera de selección y otra de enrutamiento. Las heurísticas que se presentan están basadas en el trabajo de Ratliff y Rosenthal (1983) expuesto anteriormente, y se determina que la heurística que se presentó, menos compleja que el algoritmo de Búsqueda Tabú en Daniels et al (1998), resuelve instancias de tamaño real en tiempos computacionales razonables.

En Weidinger, Boysen, & Schneider (2019) se considera un almacén de estanterías mixtas. Los autores aplican una construcción de una heurística con la cual se extiende soluciones parciales de forma gradual, con el fin de obtener valores de solución asertivos se generan muchas soluciones parciales en paralelo y solo tienen presentes las más prometedoras

dentro de un conjunto central de soluciones, también se aplica el algoritmo de Ratliff y Rosenthal (1983) explicado previamente, como un subprocedimiento para determinar el recorrido optimo del recolector circular en un almacén rectangular en donde se busca realizar el proceso de recolección de pedidos pasando por las diferentes posiciones de almacenamiento. Para resolver el problema se formula un programa de enteros mixtos que permite resolverlo con un solucionador estándar Gurobi. Luego, se presentan procedimientos de solución heurística mediante una adaptación al enfoque del vecino más cercano y un procedimiento basado en agrupaciones y dos últimas heurísticas ejecutadas con el procedimiento de mejora adicional mediante búsqueda local (NN+, piscina+).

En Masae, Glock y Vichitkunakorn (2020) se investiga acerca del proceso de preparación manual de pedidos, el cual se caracteriza por los trabajadores que deben viajar a través del almacén para realizar el proceso de picking. Se considera un almacén convencional con dos bloques, superior e inferior, donde cada bloque tiene r pasillos paralelos con igual longitud y ancho, se encuentran tres pasillos transversales; se tiene en cuenta que los puntos de inicio y finalización del recorrido de preparación de pedidos deseado puede ser cualquier ubicación en el almacén. Este tipo de modelo surge a partir de Löffler et al (2018) en donde se propone un algoritmo óptimo de enrutamiento de selector de pedidos para puntos de inicio y finalización arbitrarios en un almacén convencional con un solo bloque, es por esto que se extiende el trabajo al tener dos bloques y se soluciona mediante procedimientos propuestos en los trabajos de Ratliff y Rosenthal (1983) y Roodbergen y de Koster (2001a). Para solucionarlo, los autores proponen una heurística de enrutamiento en forma de S, enumeran los dos pasillos secundarios de selección de 1 a 2r, comienzan enumerando en el bloque superior, los pasillos secundarios de izquierda a derecha, luego en el bloque inferior de derecha a izquierda.

7 Conclusiones

El almacenamiento disperso es una estrategia que ha tomado fuerza en los últimos años, esta ha sido implementada especialmente en el segmento B2C, relacionada con el comercio electrónico, ya que éste presenta tiempos de entrega ajustados, demandas volátiles y pequeños pedidos; esta forma de almacenamiento es adecuada para este segmento, debido a que los pedidos pequeños requieren pocos artículos y el Stock de

los estantes mixtos es suficiente, pero cuando se requiere muchos artículos para cumplir con un pedido resulta contraproducente tener estantes mixtos, ya que, si el stock se agota en un estante, el selector va a tener que ir a más visitar más estantes para cumplir la orden, aumentando las distancias y el esfuerzo de la labor de recolección.

Se ha encontrado que el tema de almacenamiento es muy amplio y que en él se encuentran diversos tipos de problemas de investigación, tal como lo es el relacionado con el proceso de picking, SPRP también conocido como single picker routing problem; es importante tener claro la importancia de este tema ya que representa un gran porcentaje de las actividades laboriosas que se llevan a cabo dentro de un almacén y que repercuten significativamente en los gastos operativos. A su vez se invita a estudiar más este tipo de problema, ya que por medio de estas investigaciones se llega a analizar los diferentes tipos de almacenamiento que existen y la importancia que tiene en la era que vivimos del comercio electrónico.

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Passado, presente e futuro das operadoras refeições coletivas: Uma perspectiva econômica baseada em uma pesquisa documental e no modelo SIR de pandemia

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Resumo. Apesar de todos os esforços para contenção viral, a COVID-19 é declarada como pandemia pela Organização Mundial da Saúde (OMS). Várias medidas de contenção vêm sendo aplicadas em vários países, que de certa forma vem retardando, o número de pessoas infectadas e contribuindo para o achatamento da curva de infecção, de modo a possibilitar a priorização do tratamento de pacientes com evolução mais grave da doença. No estado do Paraná foram aplicadas medidas de contenção por meio de decretos sancionados pelo governo estadual e prefeitos municipais, onde foram suspensas as atividades econômicas não essenciais à saúde, as aulas da rede público-privada entre outras medidas, que também afetaram a população da Região Metropolitana de Curitiba (RMC), onde, no Brasil, um conglomerado composto por vários municípios é chamado de região metropolitana. As ações aplicadas para a contenção da pandemia revelaram uma problemática, que trouxeram como consequências a desaceleração da economia de várias regiões. Diante destes fatos, a pesquisa foca em analisar o impacto causado pelas medidas de contenção da pandemia COVID-19, nas operações econômicas das operadoras de refeições coletivas em 2020. Os dados da pesquisa foram coletados por meio do método de pesquisa documental baseada nas previsões do crescimento econômico para 2020 e boletins epidemiológicos. A pesquisa apresentou como resultado, os possíveis impactos, que poderá ser causados pelas medidas de contenção da pandemia COVID-19 nas operações das operadoras de refeições coletivas.

Palavras-chaves: Medidas de contenção COVID, Impacto na Economia, Prestadoras de Serviços, Refeições Coletivas.

1 Introdução

Atualmente, o vírus SARS-CoV-2 denominado como o novo *Coronavírus Disease* 2019 (COVID-19) é uma doença infecciosa causada pelo coronavírus da síndrome respiratória aguda grave (SARS) [1, 2]. Os primeiros casos de infecções surgiram no continente Asiático, no final do ano de 2019. Em 11 de Março de 2020, a Organização Mundial da Saúde (OMS) declarou o COVID-19, como pandemia e recomendou aos países ativar os mais altos níveis de protocolos nacionais de biossegurança, para garantir a contenção da disseminação viral na sociedade [3, 4, 5, 6]. A resposta global, para a contenção da pandemia COVID-19 [7, 8] e recentemente mencionada por [9] são que, as medidas de contenção aplicadas pelos países "foram muito poucas e muito tarde". Considerando o período do início dos casos até 04 Abril de 2020, as situações com a propagação da pandemia somam mais de 1.000.000 de casos confirmados e 57.206 mortes em 208 países em todos os continentes [7].

O modo rápido de transmissão da propagação do COVID-19 e a suscetibilidade da população fizeram com que esforços nacionais e internacionais para contenção da pandemia fossem ganhando ritmo [7]. Neste contexto, foram adotadas medidas de saúde pública, como reforço nas operações da vigilância sanitária, rastreamento exaustivo de contatos, distanciamento/isolamento social, restrições de viagens, fechamento de escolas, instruções sobre a higienização básica, antecipação de vacinas contra a gripe para o grupo de risco e suspensões de serviços não essenciais à saúde, de forma a contribuir para um achatamento da curva de contágio evitando a superlotação dos hospitais [4, 10]. Para conter o avanço da pandemia no Estado do Paraná, foram sancionadas determinações por meio dos decretos estaduais, (4.317/2020), que propõe medidas restritivas mais severas sobre as atividades econômicas não essenciais a saúde [10]. E o (4258/2020), que determina a suspensão das aulas de escolas e universidades públicas e privadas por tempo indeterminado [11]. As medidas estão alinhadas aos esforços, que vêm sendo aplicados em várias partes do mundo, desta forma, reforçar o enfrentamento contra a pandemia COVI-19. Neste contexto, desencadeou questionamentos propícios por meio de uma pesquisa documental baseada nas previsões do crescimento econômico para 2020 e boletins epidemiológicos, qual será o impacto das ações tomadas em terreno desconhecido para contenção da pandemia?

Sendo assim, a pesquisa foca em analisar o impacto causado pelas medidas de contenção da pandemia da COVID-19, nas operações econômicas das operadoras de refeições coletivas em 2020, baseada em uma pesquisa documental sobre o cenário econômico e a evolução epidemiológica por meio do modelo SIR epidemiológico de pandemia.

2 Procedimentos metodológicos

2.1 Objeto da pesquisa

As operadoras de refeições coletivas atuam em diversos segmentos, industriais, educacionais, hospitalares entre outros. O foco está na administração dos restaurantes internos oferecendo uma alimentação aos colaboradores.

2.2 Abordagem metodológica

2.2.1 Pesquisa documental

A pesquisa documental assemelha-se a pesquisa bibliográfica sendo a natureza, a diferença das fontes. Enquanto a pesquisa bibliográfica fundamenta-se em contribuições de diversos autores, sobre determinados temas embasados cientificamente, a pesquisa documental vale-se de materiais com fontes diversificadas, dispersas e em muitos casos não recebem o tratamento analítico de forma científica [14]. A pesquisa documental classifica-se como exploratória, pois foca em abordar um tema pouco conhecido e explorado [14] e apresenta como objetivos produzir novos conhecimentos, criar novas formas de compreender os fenômenos e apresentar, como este método desenvolve-se, para que o pesquisador possa "mergulhar" no campo da pesquisa, para obter e captar os fenômenos a partir de perspectivas contidas em documentos, para "colher" resultados e compartilhá-los no meio científico [15]. A pesquisa documental está restrita a documentos contidos em três variáveis: fontes escritas ou não, fontes primárias ou secundárias sendo classificados em contemporâneas ou retrospectivas [16].

Assim, como qualquer outro método, a pesquisa documental apresenta vantagens e desvantagens. Dentre as vantagens [14] citam-se os fatos, que estes documentos se constituem, de uma fonte rica e dados estáveis, na qual, para [15] o pesquisador poderá retirar as evidências, que fundamentam suas afirmações. Entretanto, para [14, 17] a pesquisa documental também apresenta limitações como desvantagens, as quais afirmam que os documentos são amostras não-representativas dos problemas [14]**,** mas para [18] a pesquisa documental é necessária para entender o passado para construir o futuro.

2.2.2 Modelo SIR de pandemia

O Modelo SIR (Suscetível, Infectado e Recuperado) é um arquétipo matemático utilizado para descrever epidemia proposta por Kermack e McKendrick em 1927. O modelo classifica a população em três classes: **(S)** suscetíveis: os que pode ser infectados; **(I)** Infectados: as pessoas que estão infectadas e podem transmitir a doença; **(R)** Recuperados: são aqueles curados da infecção e tornan-se imune ou morrem. Pode ser descrito da seguinte forma [19, 20, 21].

$$\frac{ds}{dt} = \text{Variação Temporal Suscetível} \qquad \frac{ds}{dt} = -\beta\ SI \tag{1}$$

$$\frac{ds}{dt} = \text{Variação Temporal Infectado} \qquad \frac{ds}{dt} = \beta SI - \mu I \tag{2}$$

$$\frac{ds}{dt} = \text{Variação Temporal Recuperado} \qquad \frac{ds}{dt} = \mu I \tag{3}$$

A manipulação algébrica, possíbilita de forma estimada verificar através de indicadores do modelo, o atingimento da taxa de produtibilidade (R_0), o qual determina a média de infecções causadas por um indivíduo contaminado. Por meio desta simplificação, as constantes BS (taxa de transmissão de infecção) e μ (taxa de recuperação) podem ser ajustadas exponencialmente, sendo assim, a taxa de reprodutibilidade (R_0) é expresso da seguinte forma [20, 21].

$$R_0 = \frac{\beta s}{\mu} \tag{4}$$

Para entender a dinâmica da pandemia considera-se R0 > 1, no qual a doença é transmitida mais rapidamente que o tempo de recuperação do infectado, tornando a população infectada. Se R0 < 1, os infectados se recuperam mais rapidamente e a vírus não tem força para se propagar e desaparece naturalmente [21, 22].

2.3 Delineamento da pesquisa

Para análise do crescimento econômico foram pesquisados relatórios sobre a previsão de crescimento do *Gross domestic product* (GDP) para 2020, publicadas entre 2º Semestre de 2019 e 1º Semestre de 2020 por instituições financeiras e de apoio a empresas, tais como: O Banco Mundial, O Fundo Monetário Internacional (FMI), O Banco Central do Brasil (BACEN), O Serviço Brasileiro de Apoio às Micro e Pequenas Empresas (SEBRAE), O Instituto Brasileiro de Geografia e Estatística (IBGE), A Associação Brasileira das Empresas de Refeições Coletivas ABERC e outras cunho regional como: Agência Estadual de Notícias do Paraná (AEN. PR), O Instituto Paranaense de Desenvolvimento (IPARDES), a Secretaria da Fazenda do Paraná entre outras. Para a simplificação do modelo SIR na pesquisa, utilizou-se dos relatórios dos informes epidemiolôgicos da COVID-19" publicados pela Secretaria Estadual de Saúde do Estado do Paraná (SESA-PR) no 1º Semestre, entre as datas de 14 de Março a 12 de Julho de 2020. Os dados coletados estão relacionados a RMC, com aproximadamente 3.615.027 habitantes [23,

24]. Para todos os cálculos e simulação matemática foi utilizado o *software Microsoft Excel®* por meio do Modelo SIR de epidemias adaptado de [25, 26, 45].

3 Análise do passado, presente e futuro

3.1 Projeção de crescimento da economia para 2020 (Passado)

A projeção de crescimento do (**GDP**) mundial prevista para 2020 é de (3,3%), um crescimento de 14% comparado ao GDP (2,9%) de 2019. Considerando a expectativa de arrefecimento entre o embate comercial sino-americano para um maior crescimento econômico mundial [27, 28]**.** No Brasil, o cenário econômico apresenta melhoras, após a recessão de 2014-2016 a economia vem obtendo crescimento. O relatório Focus apresentado pelo BACEN apresentou o crescimento de 1,2 % para o PIB brasileiro em 2019. Para [27], o crescimento para 2020 é de 2,5% com as expectativas associadas às reformas (Trabalhista e Previdenciária), já aprovadas e as discussões no Congresso Nacional sobre as novas reformas (Tributária e Administrativa), bem como à recuperação da confiança de consumidores e empresários. Segue ilustrado pela (Fig.1) o histórico e a previsão de crescimento do GDP da economia para 2020 [27, 29, 30].

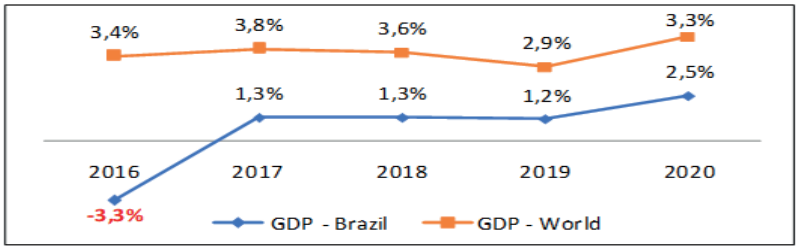

Fig.1. Taxas de crescimento (GDP) para economia em 2020, adaptado de [27, 29, 31, 30]

No Estado do Paraná, a projeção de crescimento econômico publicados recentemente (Fig.2), aponta o estado entre os cinco primeiros, com a maior participação GDP nacional com 6,4%, entre todos os estados, o Paraná, foi o que mais cresceu em 2019, aproximando-se da quarta colocação [28].

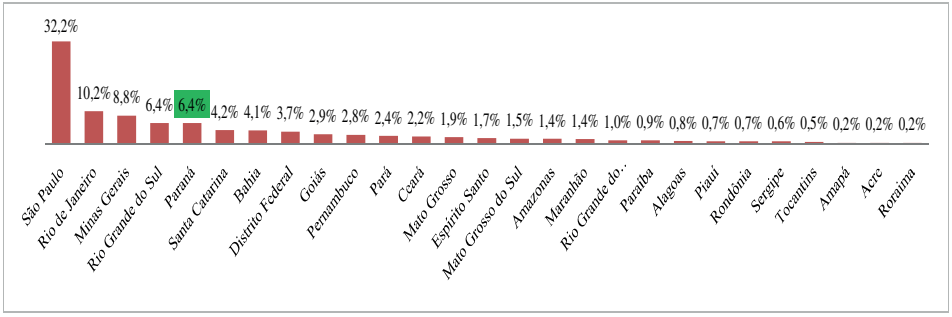

Fig.2. Taxas de crescimento GDP estados Brasileiros, adaptado de [28]

As indústrias do Paraná acumulam o segundo melhor desempenho do país, com avanços principalmente nos setores de fabricação automotivo e alimentos [32]. Apontada pela (Fig.3), o Paraná, também segue otimista, com a previsão de crescimento do GDP em 2,6% para 2020, com base na super safra de grãos do verão, com a conquista do novo status sanitário, novos investimentos em infraestrutura e o potencial para atrair novos investidores com a previsão de crescimento do GDP nacional projetado para 2,5% para 2020 [27, 33, 34, 29, 31].

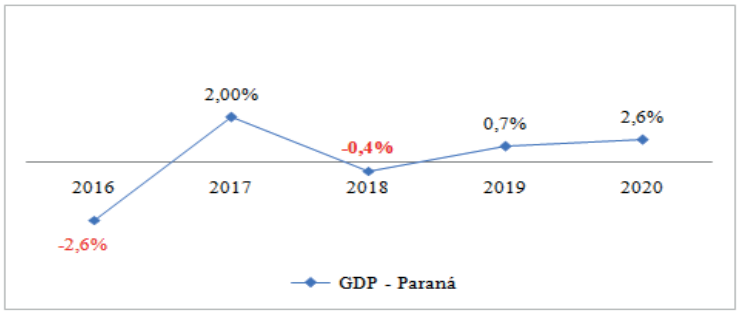

Fig.3. GPD 2020, adaptado de [34]

De acordo com a (Fig.4), o setor de refeições coletivas forneceu em 2019 um total de 426 milhões de refeições/mês movimentando cerca de R$ 20,6 bilhões/ano. O setor gerou 210 mil empregos diretos para produzir um volume de 7,5 mil toneladas de alimentos/dia e representou para os governos, uma receita de R$ 2,6 bilhões/ano entre impostos e contribuições. Para 2020, estima-se um aumento em 3,5%, elevando o número de atendimento para 441 milhões de refeições/mês, considerando um crescimento de 12% no faturamento para R$ 23,1 bilhões/ano [35].

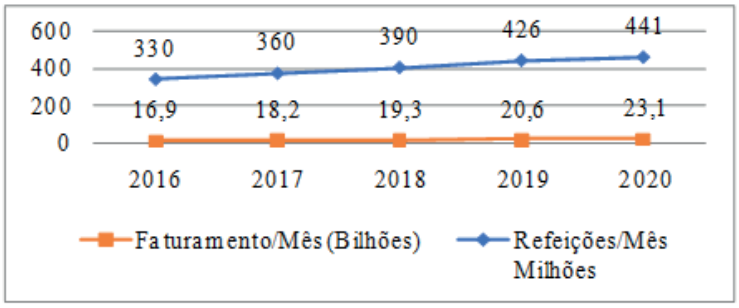

Fig.4. Dados de mercado de refeições coletivas, adaptado de [36]

3.2 Cenário econômico atual (Presente)

O primeiro caso de COVID-19 no Brasil, de acordo com a (Fig.5), foi em 26 de Fevereiro de 2020. Em (26 Março de 2020), após 20 dias do primeiro caso, o Brasil, testava positivo para 234 casos. Em 12 de março, o Estado do Paraná, registrava cinco (5) casos, todos confirmados na RMC. Como mais de 1.604 casos confirmados e 25 mortes entre os dias 17 e 22 de Março de 2020, no Brasil. No Paraná, apenas 54 infectados e sem óbitos, deste, 31 foram infectados na RMC.

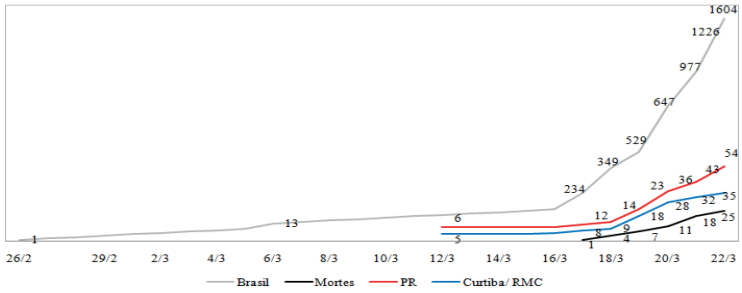

Fig.5. Evolução COVID-19, adaptado de [24, 37]

Neste cenário, o governo estadual e municipal sancionaram medidas, (tais como: isolamento social, fechamento do comércio e suspensões de aulas para rede pública e privada) para prevenção e contenção da pandemia. Neste período de quarentena, estima-se que, as operadoras de refeições coletivas tenham perdas significantes, entre 18% e 35% para o mês de Março, sendo que para o mês de Abril, as perdas poderiam chegar a 55% devido às paralisações parciais e até mesmo totais das atividades públicas e privadas. As perdas ocorrem diretamente no faturamento das operadoras, já que a cobrança é com base no número de refeições servidas aos funcionários dos clientes contratantes [37].

Observa-se (*Fig.6), ao passo que a pandemia evolui no Brasil e na RMC, medidas de contenção são tomadas precocemente, instantaneamente causa a desaceleração da economia em várias regiões, inclusive na RMC, impactando diretamente as operações das operadoras de refeições coletivas mediante a suspensão das aulas da rede pública e privada e das atividades não essenciais a saúde, também são afetados.

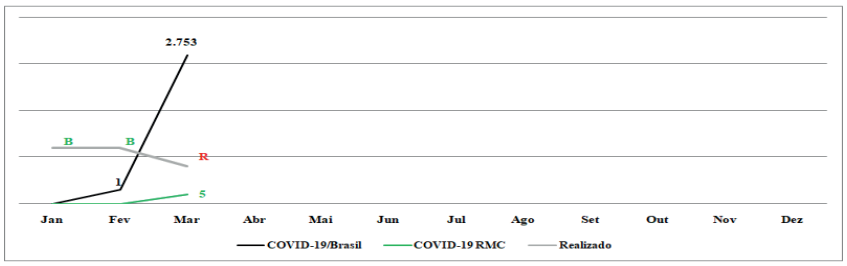

***Fig.6.** Impacto das medidas de contenção da COVID-19 nas operadoras de refeições coletivas (2020). Segue para a escala de leitura: (E) excelente (B) bom e (R) ruim.

Neste cenário, as operadoras de refeições coletivas fazem a adesão aos programas de incentivos do governo federal, estadual e municipal. São ações para mitigar os impactos econômicos gerados pelas medidas de contenção da pandemia, na busca de preservar a saúde financeira, muitas delas seguindo o movimento desemprego zero "ação de responsabilidade social" adotado por partes das empresas.

Outras notícias publicadas, relacionadas aos impactos gerados pela pandemia na economia, já trazem dados de retração de (-6,3%) no crescimento GDP mundial, o cenário de crescimento segue na contramão da previsão para 2020 de 3,3%, ou seja, uma revisão de crescimento mundial de (-3,0%), o que atinge a economia de vários países. No Brasil o impacto no crescimento é ainda maior, onde a retração está próxima dos (-7,8%). Com base, na taxa de crescimento prevista para 2,5%, que havia sido projetado em 2020, estima-se, que a retração do GDP oscilará próximo dos (-5,3%), os dados podem ser visualizados através da (Fig.7) [27, 31, 40].

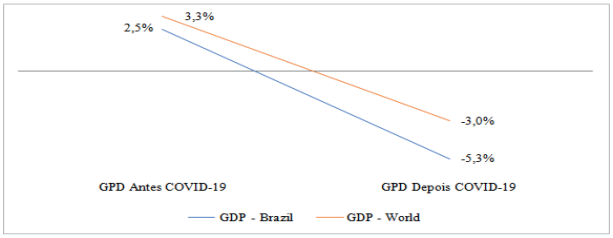

Fig.7. Taxas de crescimento (GDP) para economia, adaptado de [27, 31, 40]

A retração do GDP do Brasil reflete em todos os estados e segmentos. O estado do Paraná [34] prevê três cenários de retração: um otimista, uma base e outro pessimista. De acordo com a Tabela 1, os números são negativos e mostram que será um ano desafiador em função do desgaste econômico que estaria por vir.

Tabela 1. Previsões de crescimento do GDP para 2020, adaptado de [34]

Paraná	(GDP) 2020 antes COVID-19	(GDP) 2020 after COVID-19		
	Real	*Optimistic*	*Base*	*Pessimistc*
	2,6	-0,1	-2,9	-6,1

3.3 Contextualização para simulação de um cenário (Futuro)

A abordagem matemática elaborada por meio do Modelo SIR, para analisar hipoteticamente a evolução da pandemia, na população da (RMC), simula a evolução de contaminação de pessoas infectadas para os próximos 360 dias, com base nos casos registrados entre os dias 14 de Março de 2020 e 13 de Maio de 2020, de acordo com a Tabela 2, [24] considerando o fator de isolamento social no Estado do Paraná medido por [41] e exibido pela (Fig.8), assemelham-se com taxa de isolamento no Brasil.

Tabela 2. Números de casos confirmados RMC, adaptado de [24]

Data		Casos Confirmados	
		Infectados Acumulados	Variação Mês
0	14/mar	5	5
30	13/abr	387	382
60	13/mai	833	446
90	12/jun	2.831	1.998
120	12/jul	16.376	13.545

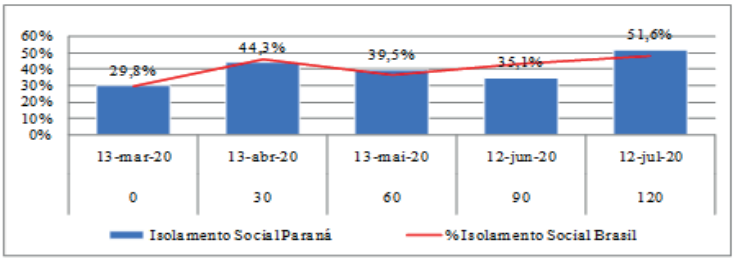

Fig.8. Taxa de Isolamento Social Paraná, adaptado de [41]

Embora o Modelo SIR possua finalidades acadêmicas e de pesquisas para descrever como a pandemia propaga-se em uma população, não se recomenda utilizá-lo como ferramenta

de tomada de descisão, já que é um modelo básico e há incertezas sobre a patologia do vírus da COVID-19, como infecções, modo de transmissão entre outros. No que tange a simulação foram considerados os parâmetros clínicos tais como a constante de recuperação $\mu = 0{,}14$ (14 dias) e o período de incubação do vírus DT = 0,5 (cinco dias) com base nos dados da *Cappra Institute for Data Science,* baseada no modelo criado pela Alison Hill, já as constantes de infecção $\beta = 0{,}23$ e os números de caso de infecção transmitida por uma pessoa infectada com $R_0 = 1{,}65$ foram geradas a partir do número de casos confirmados para região na RMC. Ilustrada pela (Fig.9), os números esperados de indivíduos infectados, recuperados, suscetíveis ao longo do tempo, já com intervenção aplicada por uma taxa média de isolamento social de 43,8% no Estado do Paraná, na qual a RMC está inserida, apontou, com base nos casos já confirmados dos primeiros 60 dias, após o primeiro caso confirmado, que aproximadamente 2.189.766 de pessoas serão infectadas no período de 360 dias, após o primeiro caso registrado, ou seja, um potencial de 60,54% da população poderá ser contaminada, com pico sendo previsto para meados de Setembro de 2020.

Obviamente, com as medidas aplicadas para a contenção da pandemia, o pico poderá ser estendido, em função de uma disseminação lenta e com o contágio sob-controle, estima-se, que o afrouxamento as medidas de contenção na RMC, possa acontecer de forma parcial, com a retomada gradual, com segurança, primeiramente na reabertura do comércio em Julho e em seguida o retorno das atividades educacionais a partir de Setembro interrompendo, segundo [42] uma sequência de quatro meses sem aulas presenciais, já que ações de ensino a distância foram aplicadas para continuidade do ensino. Dentre os planos de contenção da pandemia, outras ações para o combate a fome foram aplicadas por órgãos públicos (municipal, estadual e federal), como a contratação de empresas por meio de licitações, para o fornecimento de cestas básicas, a famílias dos alunos da rede pública de ensino e famílias cadastradas nos programas sociais de baixa renda. Estas ações contribuíram para famílias de produtores rurais e algumas operadoras de refeições coletivas, a mitigarem os impactos econômicos em suas operações [43, 44].

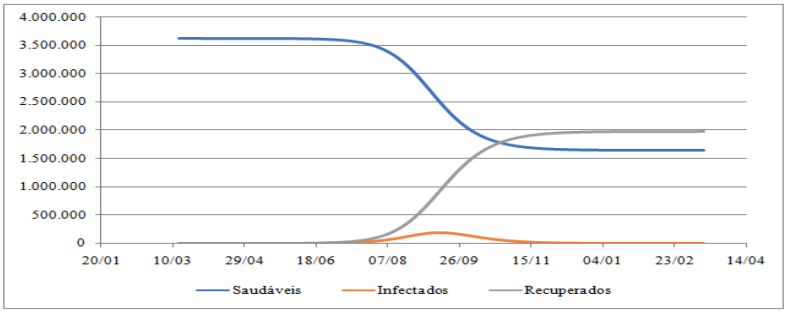

Fig.9. Simulação I - Evolução COVID-19 na população da RMC 2020

4 Análise e Discussão de Resultados

Com base nas previsões de crescimento do cenário econômico para 2020, as operadoras de refeições coletivas, projetaram um faturamento positivo para 2020, visto um cenário promissor de crescimento econômico em relação ao ano anterior (2019), não somente para Brasil, como também mundial. Como a RMC aderiu às medidas de contenção, logo no início de casos registrados, o pico da pandemia possivelmente foi achatado e provavelmente pode acontecer em meados de Setembro (Fig.9), uma segunda análise de simulação foi realizada por meio do modelo SIR, com base nos números de casos de pessoas testadas positivo entre o dia 0 (zero) 14 de Março de 2020, até o dia 120 na data de 12 de Julho 2020, o resultado apresentou similaridade ao da primeira simulação (Fig.9). Este cenário pode afetar as operações econômicas das operadoras de refeições coletivas, de Março até meados de Setembro (Fig.10) com perda parcial da receita. No entanto, considerando um retorno parcial das atividades, com o afrouxamento da quarentena aplicada, conforme observados em outros países, os resultados "Ruim", podem estender-se até Dezembro, quando agrupado ao período sazonal, ou seja, em 2020 serão apenas dois meses com resultado em escala "Bom" para os meses de Janeiro e fevereiro, antes do início da quarentena e dez meses seguidos de resultados em escala "Ruim" de queda no faturamento. Obviamente, neste período foram e estão sendo criados e executados planos de contingências e estratégias de negócios, para mitigar as perdas. Cabe lembrar que o retorno as normalidades, o aumento no faturamento também ocorrem instantaneamente de acordo com o plano público de retorno das atividades, lembrando que as receitas das operadoras são dadas em função da quantidade de clientes atendidos.

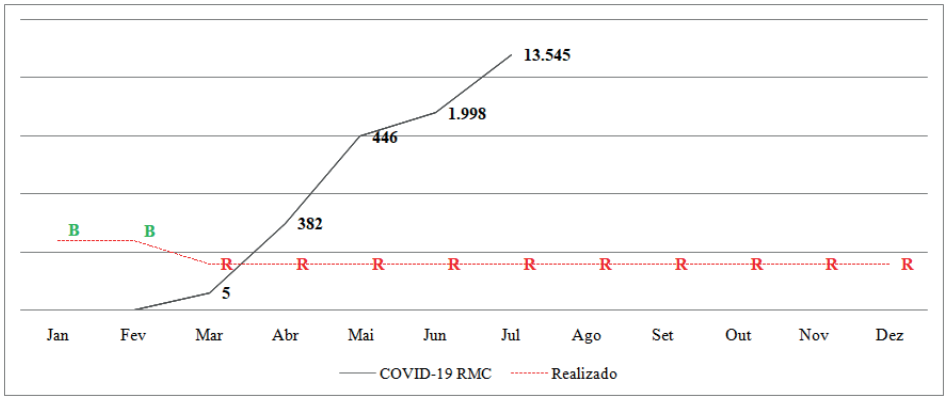

Fig.10. Impacto das medidas de contenção da COVID-19 nas operadoras de refeições coletivas (2020). Segue para a escala de leitura: (E) excelente (B) bom e (R) ruim.

5 Conclusões

O estudo retratou-se por meio de uma pesquisa documental e desenvolveu a construção do conhecimento sobre a previsão de crescimento econômico, para analisar os impactos causados pelas medidas de contenção da pandemia COVI-19 nas operações econômicas das operadoras de refeições coletivas em 2020, diante da desaceleração econômica generalizadas na região metropolitana de Curitiba (RMC).

Com o avanço da pandemia, a previsão de crescimento GDP mundial previsto para 3,0% desacelerou para -3,0. No Brasil com crescimento projetado para 2,5%, a queda prevista é -5,3%. A economia do estado Paraná prevista para crescer 2,6%, a queda estimada será de -6,1%. Duas simulações realizadas por meio do modelo SIR de pandemias, com base em dados de pessoas que contraíram o vírus a partir do primeiro caso confirmado (14 de Março de 2020) uma até o dia nº60 (13 de Maio de 2020) e a outra até dia nº120 (12 de Julho de 2020), apontam o pico de infecção para meados de Setembro de 2020, considerando todas as medidas públicas de contenção da pandemia aplicada na região com uma taxa média de isolamento social de aproximadamente 40%, bem como os parâmetros clínicos considerados na metodologia de aplicação. Cabe mencionar, que as medidas de contenção sendo mantidas sempre empurram o pico da curva para frente, com um menor número de pessoas sendo infectadas no período.

As operadoras foram impactadas diretamente e a partir do início da quarentena vem apresentando resultados ruins por meses seguidos. Neste período, já somam 120 dias, até 12 de Julho de 2020. As operadoras de refeições coletivas vêm buscando alternativas para mitigar as perdas, como, adesão aos programas sancionados pelos governos (Municipal, Estadual e Federal), para preservar os caixas das empresas, à medida do possível, desenvolvendo estratégias para a manutenção dos negócios entre outros. Conforme observado em outros países, como a Itália, China, Espanha entre outros, o retorno as atividades vêm acontecendo de forma gradativa. Estima-se que as operadoras de refeições coletivas apresentem resultados em escala de (R) ruim, de Março á Dezembro de 2020, ou seja, dez meses consecutivos de resultados abaixo do esperado.

O segmento de alimentação é forte, mas assim como todos os outros, o ciclo de vida está ligado à cadeia de valores, onde um alimenta o outro, em questões econômicas. Num futuro próximo, com as pessoas adaptando-se a uma nova forma de viver e a vacina para combater o vírus da COVID-19, já em fase de teste, seja disponibilizada a população, tão logo, a vida volta ao “novo normal” e as empresas vão recuperando suas economias adaptando-se a um novo conceito de vida, deixado pelo legado da pandemia.

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An operational planning model to support first mile logistics for small fresh-produce growers

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Abstract. In this work, we propose a hierarchical optimization model to support har-vest and local routing decisions of fresh agricultural products. The proposed model has been motivated by the fact that small growers of fresh produce very often face difficulties in terms of availability of local (or first-mile) logistics at reasonable prices which results in lower profit margins and more food waste. So, in order to reduce the cost of first-mile logistics they can co-ordinate the consolidation of the harvests from different growers to send their products to the packing facility. Hence, we integrate harvesting and routing operations for a set of small growers with the aim to reduce their operational costs. The proposed framework has been implemented and preliminary evaluated with some instances considering as case study farmers of fresh produce in the central region of Chile.

Keywords: First mile logistics · Small fresh-produce growers · Harvesting and distribution planning

1 Introduction

Fresh fruit and vegetables consumption have been growing in recent years worldwide. The combination of the growth of global population, nutrition concerns and more open borders will sustain, if not accelerate, the current growth of international trade of fresh fruits and vegetables. As an example, Figure 1 presents the imports of fresh fruits and vegetables into the US for consumption, from 2015 until 2019 expressed in thousands of US dollars. We can observe that in both cases, the graph shows a remarkable increasing trend.

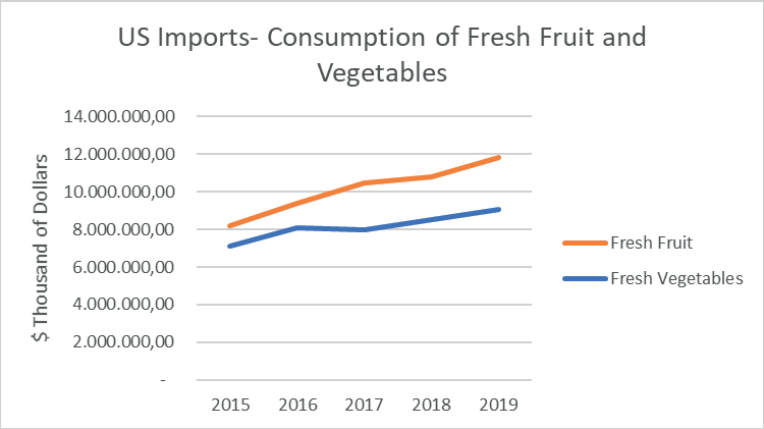

Fig. 1. US Imports for consumption of fresh fruit and vegetables (Thousand of Dollars). Source: Source: FAS- USDA database, accessed on August 13th, 2020.

This expanded demand of fresh fruits and vegetables represents a challenge since it requires the development of efficient supply chains that can meet this increasing demand considering all the complexities derived from the perishability of the product. Hence, the transportation, storage and distribution of these products need to be carefully planned to minimize food waste due to inefficient logistics practices. This opens the question of how to reengineer traditional supply chains for fresh produce into flexible and rapid response supply chains to best serve the rapidly changing market.

The covid-19 pandemic has caused serious problems in the supply chains of agricultural products. For instance, the media has reported cases of lack of food at the supermarket shelves and crops being wasted at the farms because of lack of traditional markets, such as food service outlets, for the farmers[12]. Furthermore, there has been shift of consumption to supermarket chains and direct-to-consumer channels. This highlights the need to develop tools to make rapid logistics connections between farmers and the evolving markets. This is even more relevant in the case of small growers who very often face additional challenges. For instance, even prior to the pandemic, small growers were experiencing difficulties accessing some markets, due among other factors to poor logistical channels, lack of negotiation power and lack of access to financial resources. Furthermore, due to some food safety regulations and first-mile logistics challenges, usually supermarket chains do not procure directly from small growers. Some of the changes caused by covid-19will be permanent and hence, we need to prepare for the new conditions.

Currently, very often two or more intermediaries take possession of the product between the farm's gate and the final consumer, resulting in multiple locations holding

[11] https://www.magazine.bayer.com/en/feeding-the-world-in-a-pandemic-can-food-supply-chains-cope-with-covid-19-.aspx
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inventory throughout the supply chain. In this case, customers and growers are not directly connected to the final market, and are limited to operate under the market signals transmitted by those intermediates which results in distorted market information and, capturing a lower margin of the value chain than if they would sell directly to the final consumer. The long distribution chain also contributes to the high levels of waste observed in the fresh produce industry. Accordingly, improvements in the fresh food supply chains, may provide social benefits that range from higher income for small and regional farmers, to more abundant healthy food for the consumer [1].

Figure 2 presents a schematic view of the main processes of a fresh produce SC. The main echelons of a prototypical fresh produce supply chain are indicated, as well as the physical flow of products through it [2].

	Agricultural practices and Harvesting	Consolidation & Cold-Chain Entry	Processing / Packing	Transportation and logistics	Final Distribution Logistics
Strategic Decisions	• Selection of farming technology & equipment • Financial planning • Design of supply networks, • Evaluation of perennial crops, Crop rotation strategies	• Selection of storage equipment & technology • Financial planning • Design of supply networks • Selection of cold technology • Location of cold chain facilities	• Selection of storage equipment & technology • Financial planning • Design of supply networks	• Design of the global supply chain network • Design of the domestic supply chain network	• Design of supply network • Market selection and contracts with customers (incoterms and other conditions) • Pricing analysis
Tactical and Operational Decisions	• Cropping planning • Harvesting planning • Planting policies • Equipment scheduling • Water allocation • Land preparation • Labor planning	• Storage planning • Cold chain scheduling and planning • Transportation planning and scheduling • Plan opening chambers	• Storage planning • Cold chain scheduling and planning • Transportation planning and scheduling • Batch production planning • Load assignments • Packing	• Domestic transportation planning and scheduling • International transportation planning and scheduling • Packing and unpacking • Inventory decisions and cargo handling • Empty container logistics • Clearance and other procedures management	• Transportation planning and scheduling • Packing and unpacking • Inventory decisions and cargo handling

Fig. 2. Schematic view of the main processes of a fresh produce supply chain. Source: Villalobos et al. [2].

In this paper, we aim to provide planning tools for small growers based on an integrated planning and coordination environment for supply chains of fresh fruits and vegetables that includes information acquisition and coordination supply-demand tools to close the logistics and information gap between small growers and existing and emerging markets, especially those created by direct sales to consumers through ecommerce. The aim is to increase the benefits obtained by the small growers by means of a coordination

scheme in their first mile operations. We focus on the operational planning decisions related to the harvesting and transportation of produce to the packing facilities. In particular, we propose a hierarchical planning decision model to determine joint harvest and truck scheduling for a group growers. We apply the proposed model to a case study that consists of small growers that produce fruits and vegetables in the central region of Chile. The underlying problem is to coordinate harvest and truck routing to achieve cost savings in first mile logistics, which it is usually one of the main hurdles for the integration of small farmers have to solve to insert themselves into the main marketing channels.

The remainder of this paper is organized as follows. Section 2 presents a literature review regarding operational harvesting and transportation decisions of a fresh produce supply chain. Section 3 presents the proposed mathematical formulation. Section 4 presents the experimental design and numerical results. Conclusions and recommendations for future research are given in Section 5.

2 Literature review

Research on agricultural supply chains have gained the attention of academics in several aspects. There are many planning decisions in a fresh-produce agricultural supply chain at the strategic, tactical, and operational level. We can find multiple contributions addressing different planning aspects [3-17]. Comprehensive reviews of operational research tools to support planning decisions can be found in [18,19] and Villalobos et al., [1] present a review of technologies to support real-time decisions for fresh produce logistics.

Among strategic level decisions, we can refer to Flores and Villalobos [8] who focused on the development of market intelligence tools. They developed an opportunistic shipment policy that increases a farmer´s commercialization reach within a secondary market with minimal or no capital investment once a base market has been established. From the perspective of the first mile decisions, we can refer to Ahumada et al. [4] that present an integrated tactical planning model for the production and distribution of fresh agricultural problems under uncertainty. The proposed model aims to maximize the revenues of a single and large producer that has some control over the logistics decisions associated with the distribution of the crop.

Ahumada and Villalobos [3] on the other hand, propose an operational model for planning the harvest and distribution of perishable agricultural products considering a single large grower. The aim of the work is to optimize the savings provided by the trade-off between the freshness with which the products are delivered and the transportation costs. The model generates short-term decisions related to harvesting, packing and transportation. They consider time constraints, available labor, and the effects of harvesting decisions on product quality; their modeling strategy is based on harvest

patterns and one of the decisions considered is which pattern should be used for harvesting each plot of the planted area. The model takes the perspective of a single grower who produces tomato and bell peppers.

Ferrer et al. [7] propose an optimization approach for scheduling wine-grapes harvest operations. They propose a mathematical model that schedule the harvesting operations considering the quality loss due to harvesting before or after the optimal date. They consider penalizations for harvesting before or after the optimal date. This is an important difference with respect to the work to be presented in this paper. Rather than modeling the initial and final harvesting times, in this paper we consider patterns that determine the frequency of the harvesting along the days of the planning horizon. For instance, one harvesting pattern corresponds to harvesting every single day, another corresponds to harvesting every other day, and so on.. . Ferrer et al. [7] consider routing aspects into their model, as they assume that equipment and personnel should be moved from one block of the planted area to another. They model the routing problem as a TSP (Traveling Salesman Problem). This is another difference with respect to our work in which we consider more than one vehicle to transport the fresh produce from the small farms to a packing center.

In terms of previous works in the literature that specifically consider small growers, we can refer to Flores et al. [9]. They propose a framework for the strategic design of local agricultural systems for small growers. In terms of contributions focused on the transportation of harvested products, we can refer to Alarcon-Gerbier et al., [11]. They address the combined problem of fresh produce harvest-decisions and the scheduling of truck arrivals to processing plants of tomato. González-Araya et al. [12] consider the same problem and propose a GRASP methodology for solving the model. Although it has certain similitudes to our work, they consider a problem with different objectives than those considered in the models to be presented in this paper. For instance, their objective function is based on the minimization of waiting times of trucks, while we aim to reduce total costs.

Another related contribution is presented by Yantong et al. [13] who propose an inventory routing planning model for perishable food with quality considerations. They consider the case of sending products to different retailers from a single depot, focused on the last mile logistics, that differs from our case that focuses on first mile activities. Furthermore, they do not consider labor restrictions which is an important aspect include in our model.

Lamsal et al. [14] address the integrated harvest and delivery scheduling problem for planning the movement of the crop from the farm to a processing plant. They consider the case of multiple and independent producers and assume that no on-farm storage is allowed. They consider a time-frame of 24 hours. In contrast, in our case we assume a longer planning horizon (for instance, 2 weeks) to coincide with the planning of harvesting operations observed in practice. Furthermore, while in our case, we are

maximizing profits, their model penalizes positive and negative deviations from the mill´s unloading capacity.

Gvozdenovic and Brcanov [15] address the problem of transporting agricultural goods from the fields to the factory using a fleet of vehicles. They consider the transportation of sugar beets used in sugar production. The transport between the fields and the factory is modeled by a time-span network. They do not consider harvesting decisions, which is an important difference with respect to our work.

Another related work is presented by Plessen [16] that addresses a tactical decision problem for harvest-planning based on the coupling of crop assignment with vehicle routing. They determine which crop to assign to each field, the sequence to serve the fields during the harvest and the dispatching of multiple harvesters located at multiple depots to the multiple fields. One important difference is that in our case we consider an operational planning decision model and assume that crops have been already planted. Furthermore, we are not considering the dispatching of harvesters but consider a limited labor available.

Jiang et al. [17] propose an integrated harvest and distribution scheduling model considering time windows for perishable products. The distribution of products is done directly from the farms to the consumers. They consider a single farm and several consumers located in different places, which is the main difference with respect to our work. In our case we assume that products are transported to a packing facility from which they will be transported to a distant location. They consider a single type of product while in our case we allow multiple products. Another important difference is that they model the scheduling problem based on the initial and final time of harvesting at the farm, while in our case, the timing is determined by the harvesting patterns selected which simplifies the modeling structure.

In this paper, we aim to extend the operational planning model proposed by [3] to consider small growers that are organized by a supply chain coordinating agent who uses planned routes for consolidating cargo instead of using direct shipments. In contrast to the most of the existing related literature, we consider a planning horizon of several days, and harvesting patterns as the planning cornerstone as it is done by [3].

3 Mathematical formulation and proposed solution approach

We consider the problem of planning the harvesting and distribution of fresh products from several small farmers to a packing facility. We propose a hierarchical approach based on two stages that are iteratively solved, as it is illustrated in figure 3. The first step consists of solving the harvest planning model, estimating the distribution costs as a direct shipment. Once the harvesting decisions have been made, a routing model is solved to consolidate shipments from several growers. The solution of the routing

problem provides the transportation costs to the harvesting model. The procedure is repeated until both models converge.

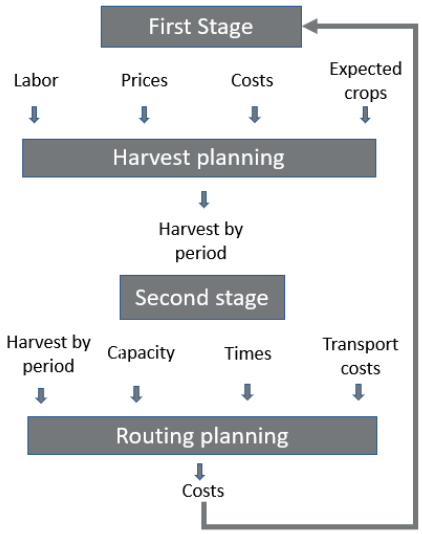

Fig. 3. Hierarchical solution implementation.

Sections 3.1 and 3.2 present the harvesting and routing mathematical formulations are respectively.

3.1 Harvesting planning model

We consider the planning problem of harvesting and distributing products by means of consolidated routes serving *I* farms and delivering the consolidated cargo to a single packing facility. Each farm produce K products. As in Ahumada and Villalobos [3], in order to simplify the model, we define harvesting patterns as the basic planning unit. Each harvesting pattern has different labor requirements and results in different amounts harvested. Then the harvesting decision problem consists of determining the timing and the harvesting pattern to be used to by each grower so that profits are maximized. Thus the problem becomes what harvesting pattern (if any) to use every day to harvest all the fruit that is ripe that day. We assume that only one pattern can be used in a single day for each planted plot. According to the products planted, it is expected certain volume of products to be harvested in each farm. The available labor for each farm is restricted, and for each box of product harvested is necessary certain hours of labor, which is also equivalent to cover a hectare of product in each farm. Each product has a minimum demand to be covered. We aim to maximize profits for the farmers, assuming a certain price for the products to be sent to their market as well as certain price of the product savage. Harvested products are transported to a packing facility, so

we also consider the corresponding transportation costs. The notation employed is further described.

Sets and Parameters
$t \in T$: planification periods (days).
$k \in K$: products.
$i \in I$: farms.
$v \in V$: harvest patterns.
EH_{tikv}: expected harvest in period t from farm i of product k by pattern v (in boxes of product).
SH_{tv}: if the pattern v is required to harvest in period t.
VS_{tk}: percentage of product k which is discarded in period t.
LAH_{it}: available labor for the farm i in period t.
LRH_{ik}: hours needed to harvest a box of product k in farm i.
LBH_{ik}: hours of labor necessary to cover one hectare of product k in farm i .
MOP_i: maximum working hours per farm i.
D_{kt}: minimum quantity to send of product k in period t.
P_{kt}: price of the product k in period t.
PS_{kt}: price of the product k salvaged in period t.
CH_k: cost of harvesting a box of product k.
$Clabor$: cost of one hour of work.
CT_i: estimated cost of transporting a box to the consolidation center from farm i .
Cap: truck capacity.

Variables
X_{tikv}: harvested area of product k in the farm i with harvest pattern v in the period t.
QH_{tik}: harvested boxes of product k from farm i in the period t.
SP_{tikr}: shipped boxes of product k from farm i in the period to the consolidation point, using truck r.
QS_{tik}: discarded boxes of product k from farm i in the period t.
Opl_{it}: hours of labor contracted in the farm i in the period t.

The proposed model is formulated as a mixed integer programming (MIP) model as follows:

$$Max(\sum_t \sum_i \sum_k \sum_r SP_{tikr}\, P_{kt}) + (\sum_t \sum_i \sum_k QS_{tik}\, PS_{kt} - (\sum_t \sum_i (LAH_{it} + OPL_{it}) Clabor) - (\sum_t \sum_i \sum_k QH_{tik} CH_k) - (\sum_t \sum_i \sum_k \sum_r SP_{tikr} CT_l) \quad (1)$$

Subject to:

$$QH_{tik} = \sum_v X_{tikv} EH_{tikv} \quad \forall\, t, i, k. \quad (2)$$
$$QH_{tik} \leq Cap \quad \forall\, t, i, k. \quad (3)$$
$$QS_{tik} = \sum_v X_{tikv} EH_{tikv} VS_{tk} \;\forall\, t, i, k. \quad (4)$$
$$\sum_k (LRH_{ik} QH_{tik}) + \sum_k \sum_v X_{tikv} SH_{tv} LBH_{ik} \leq LAH_{it} + OPl_{it} \quad \forall\, t, i. \quad (5)$$

$$\sum_r SP_{tikr} = QH_{tik} \quad \forall\, t,i,k. \tag{6}$$
$$\sum_i \sum_r SP_{tikr} \geq D_{kt} \quad \forall\, t,k. \tag{7}$$
$$\sum_v \sum_t X_{tikv} \leq AP_{ik} \;\forall\, i,k. \tag{8}$$
$$Opl_{it} \leq MOP_i \quad \forall\, t.i. \tag{9}$$
$$\sum_i \sum_k SP_{tikr} = Cap \;\forall\, t,r. \tag{10}$$
$$X_{tikv}\,, QH_{tik}, SP_{tikr}, QS_{tik}, Opl_{it} \geq 0 \;\forall t,i,k,v,r. \tag{11}$$

The objective function (1) maximizes the benefits of selling the normal and the salvage products minus the cost of labor, harvest and transport. Constraint (2) indicates that the amount harvested depends on the area harvested according to the pattern and the expected harvest. Constraint (3) limits the harvest to the truck capacity. Constraint (4) indicates that the quantity of the product discarded depends on the area harvested according to the pattern, the expected harvest and the estimate of the quantity discarded. Constraint (5) limits the quantity harvest to the labor available. Constraint (6) define that all the quantity harvested must be send. Constraint (7) indicates that the quantity sent to destination must be at least the minimum quantity. Constraint (8) limits the area harvested per pattern to the total area planted. Constraint (9) indicates that the extra labor is limited to a maximum working hours per day. Constraint (10) limits the quantity sent to the truck capacity. Constraint (11) indicates the nature of the variables.

3.2 Routing problem

The second phase of the hierarchical approach consists of a planning problem for the recollection of the harvests from a set of farms located in different locations. Each one of these farms harvests a given quantity of products in a determined period of time according to a preestablished plan. The aim is to send all the products harvested by the farmers to a packing center, minimizing the costs of transportation. A fleet of trucks with limited load capacity is available to do the transportation of products. Time windows are defined for the collection of these products, as well as the operating times of the packing facility.

Parameters

$r \in R$: trucks.
$I_0 = I \cup \{0\}$, where the node 0 corresponds to the packing facility.
HS_{ti}: amount of harvest to send from the farm i in the period t.
Cap: trucks capacity.
TBF_{ij}: Travel time between farms (i,j).
C_{ij}: Travel cost between farms (i,j).
S_i: Charging time in the farm i or discharge at the consolidation point.
E_i: Earliest time to get to the farm i.
U_i: Later time to get to the farm i.
M: Scale very large.

Variables

X_{tijr}: if the arc (i,j) is visited by the truck r the period t.
Y_{tir}: if the farm i is visited by the truck r the period t.
VT_{tir}: time to visit the farm i by the truck r the period t.
$VTCE_{tr}$: departure time from the consolidation point by the truck r the period t.
$VTCA_{tr}$: time of arrival at consolidation point by the truck r the period t.

Objective function

$$Min \sum_t \sum_i \sum_j \sum_r C_{ij} X_{tijr} \quad (12)$$

Constraints

$$\sum_i X_{tizr} - \sum_j X_{tzjr} = 0 \ \forall z,r,t. \quad (13)$$
$$\sum_i Y_{tir} \leq \sum_i X_{t0ir} M \ \ \forall \ r,t. \quad (14)$$
$$\sum_i Y_{tir} \leq \sum_j X_{tj0r} M \ \ \forall \ r,t. \quad (15)$$
$$\sum_i HS_{ti} Y_{tir} \leq Cap \ \ \forall r,t. \quad (16)$$
$$\sum_{j!=i} X_{tijr} = Y_{tir} \ \ \forall i,r,t. \quad (17)$$
$$\sum_{i!=j} X_{tijr} = Y_{tjr} \ \ \forall j,r,t. \quad (18)$$
$$\sum_r y_{tir} M \geq HS_{ti} \ \ \forall i,t \ where \ i \in I: HS_{ti} \geq 0. \quad (19)$$
$$\sum_r y_{tir} = 1 \ \ \forall i,t \ where \ i \in I: HS_{ti} \geq 0.$$
$$VT_{tir} + S_i + TBF_{ij} - \left(1 - X_{tijr}\right)M \leq VT_{tjr} \ \ \forall \ i,j,r,t. \quad (21)$$
$$VTCE_{tr} + TBT_{0j} - \left(1 - X_{t0jr}\right)M \leq VT_{tjr} \ \ \forall j,r,t. \quad (22)$$
$$VT_{tir} + S_i + TBT_{ij} - (1 - X_{ti0r}) \leq VTCA_{tr} \ \ \forall \ i,r,t. \quad (23)$$
$$E_i \, y_{tir} \leq VT_{tir} \leq U_i \, y_{tir} \ \ \forall \ i,r,t. \quad (24)$$
$$E_o \leq VTCE_{tr} \ \ \forall \ r,t. \quad (25)$$
$$VTCA_{tr} \leq U_o \ \ \forall \ r,t. \quad (26)$$
$$VT_{tir}, VTCA_{tr}, VTCE_{tr} \geq 0 \ \ \forall \ i,r,t. \quad (27)$$
$$X_{tijr}, \ Y_{tir} \in \{0,1\} \ \forall \ i,j,r,t. \quad (28)$$

The objective function (12) minimize the transportation cost from all farms to the consolidation center. The constraint (13) defines the correct flow of the trucks. The constraint (14) and (15) indicates that each route must start and finish in the consolidation center. The constraint (16) limits the amount sent to the truck capacity. The constraints (17) and (18) defines the relation between variables X_{tijr} and Y_{tir}. The constraint (19) indicates that if there is a harvest to be removed, the truck must visit the farm. The constraint (20) restrict to visit once each farm that has harvest. The constraints (21), (22) and (23) defines times of arrival between farms, to a farm from the consolidation center and to the consolidation center. The constraint (24) restrict the time of arrival to each farm. The constraints (25) and (26) restrict the time of departure and arrival to the consolidation center. The constraints (27) and (28) define the nature of the variables.

4 Experimental design

To evaluate the performance of the proposed framework numerical experiments were carried out. The instances were generated considering six factors that were varied using two levels (low and high): the number of farms (I), the cost of harvesting a box (CH_k), the available extra working hours (MOP_i), the harvest yield (EH_{tikv}), the capacity of the trucks (Cap) and the labor cost ($Clabor$). This resulted in an experimental design of 2^6, that is, 64 different instances. The values of the parameters were estimated according to information provided by INDAP (Chilean Agricultural Development Institute) website and interviews with technical personnel of this Institute.

Table 1. Parameters used in the experiment

Parameter	Low Level (-1)	High Level (1)
I (Farms)	4	6
CH_1 (USD)	\$1.55	\$1.705
CH_2 (USD)	\$0.43	\$0.473
CH_3 (USD)	\$1.5	\$1.65
MOP (hours)	120	150
EH_{ti1v} (boxes)	9,000	11,000
EH_{ti2v} (boxes)	5,400	6,600
EH_{ti3v} (boxes)	540	600
CAP (boxes)	1,000	1,800
I (Farms)	\$3.28125	\$3.9375

For each of the instances, 6 replicates were created, in which the yield of the harvest varies 10% of the expected yield for each level and product. The location of the farms was set considering the central region of Chile. The location of the farms was defined by using google maps and the areas were the products grow in the central region of Chile (the Metropolitan Region of Santiago and the Region of Valparaiso).

The proposed optimization framework was implemented in Phyton version 3.7.6 with the AMPL 2.0 API. Gurobi 5.0.1 solver is used to solve the mathematical models. To solve the experiments, an MSI computer with an Intel Core i7-7700HQ CPU 2.80 GHz, with 8 GB of installed memory and Windows 10 with a 64-bit system is used.

Due to the computationally difficulty of solving the routing model, the number of farms was limited to 4 and 6 farms (in the low and high-level values). The computational results are presented. Table 1 which shows the minimum, maximum and average times to solve the instances.

Table 2. Computational times (seconds).

	Minimum	**Maximum**	**Average**
Harvesting time (s)	0.15	0.80	0.18
Routing time (s)	0.17	22.80	0.95
Total time (s)	1.70	25.39	3.10

Table 3 presents the benefits obtained when consolidating products for the transportation from the farms to the packing facility, considering the values (low and high) of each parameter, as well as the general results. The table presents the increase (%) of profits with respect to the direct shipment strategy where each farm transports their products without any coordination with other growers.

Table 3. Numerical results in terms of profits increase.

	Profit Increase (%)		
	Minimum	**Maximum**	**Average**
Overall results	9.20%	26.02%	16.81%
Profit Increase by Factor			
Farms			
-1 (low level)	9.20%	11.22%	10.00%
1 (high level)	21.63%	26.02%	23.63%
Box Cost			
-1	9.21%	25.81%	16.81%
1	9.20%	26.02%	16.82%
Labor Hours			
-1	9.20%	26.02%	16.92%
1	9.24%	25.62%	16.71%
Yield			
-1	9.47%	26.02%	17.52%
1	9.20%	23.79%	16.11%
Capacity Truck			
-1	9.20%	16.28%	16.28%
1	9.87%	17.35%	17.35%
Labor Cost			
-1	9.23%	26.02%	16.82%
1	9.20%	25.74%	16.81%

We performed an analysis to determine the factors that are more relevant in increasing the profits of the small growers. We found that the most relevant factors were the number of farms, the harvest yield, and the truck capacity (see Fig. 4). As the number of farms increases, the profits of the farmers increase due to the reduction of logistics costs.

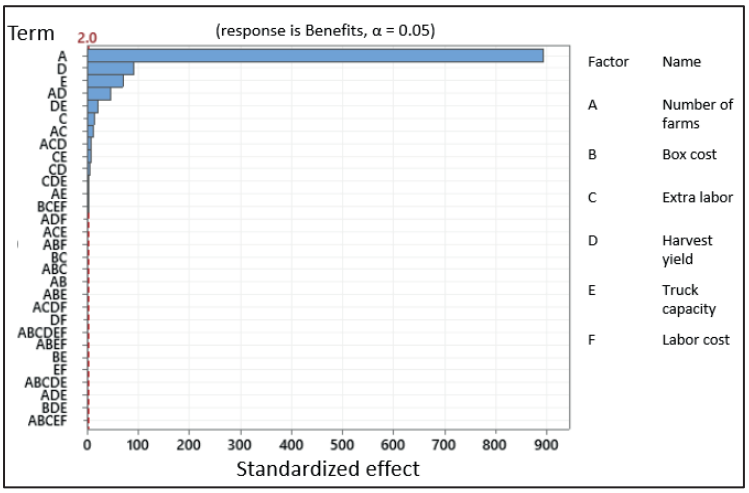

Fig. 4. Pareto chart of the Standardized Effects on the experimental design 2^6.

As an example, we present the routes found in one of the instances solved by the proposed optimization framework. This instance corresponds to 4 farms that produces strawberries and cauliflower. The percentage of profit increase in the final solution with respect to a direct shipment strategy is 10%. Figure 5 presents the routes found in the optimal solution. Figure 5a presents the route of truck 1 which starts in the packing center (blue point D), then goes to farm 2 (red dot B), continue to farm 1 (red dot C) and finally return to the packing center. Figure 5b presents the route of truck 2 that initiates the route with the farm 4 (yellow dot B), departing from the packing center (blue dot D). Then it visits the farm 3 (yellow dot C), to finally return to the packing center.

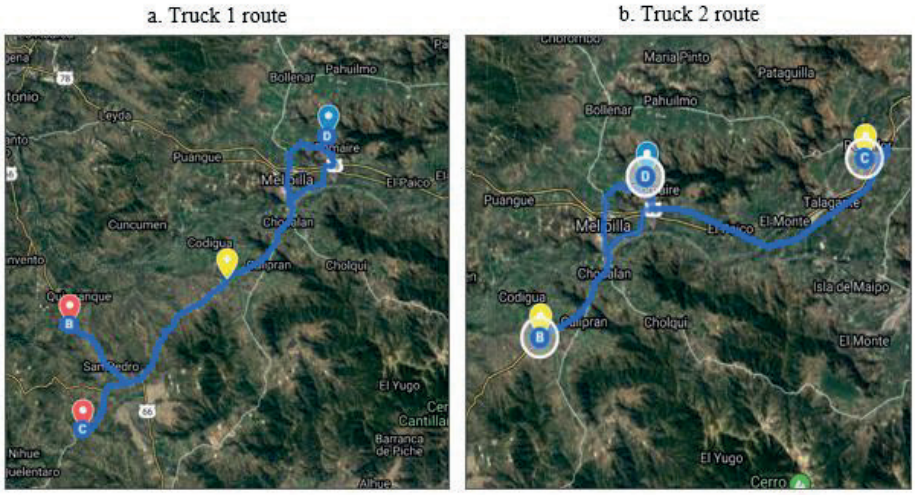

Fig. 5. Illustration of the routes found in one of the instances solved.

5 Conclusions

In this work, we presented an optimization framework to support first mile operations considering the case in which small growers coordinate the transportation of fresh products to a packing facility. We hierarchically integrated the harvesting and routing decisions. A reduced version of the harvesting planning model proposed by Ahumada and Villalobos [1] was used, considering harvesting patterns and labor availability restrictions. The routing model is a classical VRP with time windows. The proposed solution framework was implemented in Phyton and Gurobi. An iterative scheme was used to integrate the harvesting and routing models. Preliminary testing was performed considering small instance sizes only, given the complexity to optimally solve the large routing models. Results provide insights in terms of the profit increase obtained by coordinating the transportation of products from the farms to the packing center, in comparison to direct shipments of the farmers. This illustrates the benefits that small farmers can achieve if they can be organized in a cooperative scheme that may support the logistics operations. Results also show that the most significant factors that impact the profits increase are the number of farms, and then, the capacity of the trucks.

As ongoing research, we are considering several aspects to improve the routing model to apply to more realistic aspects. For instance, we plan to allow cargo splitting to better use the capacity of the trucks. We are also evaluating alternatives that can reduce the computational time of the routing model, such that providing an initial solution to the solver based on a heuristic algorithm. In terms of the harvesting model, as we have simplified the model proposed by Ahumada and Villalobos[3], we are evaluating some extensions that include the incorporation of perishability and quality aspects in the model, as well as compatibility of the products.

Further research should consider the integration of a tactical planning model as the one proposed by Ahumada and Villalobos[4] with the operational planning model so that the planting and harvesting decisions can be related to the coordination with first mile logistics. Cooperative schemes and negotiations among the small farmers to incorporate into the models should also be explored.

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Digital Twin e PHM para Otimização de Níveis de Inventário

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Resumo. A manufatura inteligente associada ao advento da indústria 4.0 marcam uma nova era associada a soluções tecnológicas, onde sistemas físicos e virtuais (CPS) são empregados para aperfeiçoar processos e operações em um ambiente altamente competitivo. Nesse contexto, digital twin (DT) e prognóstico e gestão de saúde de ativos (PHM) desempenham um papel fundamental na manufatura permitindo através de monitoramento e análise por meios físicos e virtuais, maximizar o uso de ativos com estimativa de vida útil restante (RUL) e minimizar interrupções não programadas. Esse artigo propõe uma extensão a esse contexto abordando a otimização do inventário de materiais e peças de reposição, que representa um valor significativo que por muitas vezes fica imobilizado sem previsão de uso, causando um impacto financeiro nas organizações. É avaliado na literatura o uso de DT e PHM relacionado ao controle de peças de reposição, bem como lacunas encontradas e oportunidades a serem abordadas.

Palavras-chave: Digital twin, PHM, RUL, Peças de reposição

1 Introdução

Atividades de MRO (Manutenção, Reparos e Operações) são consideradas essenciais para uma operação adequada de ativos industriais, e consequentemente um desempenho superior na manufatura de produtos. Embora amplamente reconhecida como uma atividade essencial, seu custo operacional tem um impacto financeiro relevante nos processos de manufatura criando um trade-off entre a necessidade e o custo resultante. Além dos valores resultantes das atividades de planejamento, execução e reparo, ainda há o acréscimo do custo de inventário dos itens utilizados que nem sempre é transparente nas organizações.

Contudo, com o advento das novas tecnologias de informação que possibilitaram o surgimento da internet das coisas (IoT) e a 4ª revolução industrial (indústria 4.0), corroboram para o desenvolvimento de soluções para maximizar o resultado das atividades de MRO com um custo adequado à manufatura.

Uma das soluções em potencial que tem recebido uma expressiva atenção de pesquisadores, além dos players e indústria, é o Digital Twin (DT) que teve o conceito

desenvolvido inicialmente no campo aeroespacial [1] e com um número de publicações crescentes em aplicações complexas como manutenção de aeronaves e usinas geradoras de energia [2]. Embora em um menor número de publicações, recentes esforços na pesquisa têm sido encontrados utilizando a abordagem de DT para manufatura e manutenção industrial [1, 3, 4] e alinhados com o conceito de manufatura inteligente (smart manufacturing).

Enquanto DT desempenha um papel importante no desenvolvimento da manufatura inteligente, PHM (Prognostics and Health Management) representa um avanço nas técnicas de manutenção baseada na condição (CBM), indo além do monitoramento do estado de um componente ou sistema de um equipamento. A combinação de dados históricos, monitoramento on-line e uso de algoritmos, permitem que PHM possa estimar a vida útil restante (RUL) de um componente, além da predição de falhas futuras [5, 6, 7, 8].

Há um número crescente de pesquisas sobre esses temas com diferentes objetivos como o aumento de performance e confiabilidade dos ativos utilizados na manufatura, bem como a redução dos custos relacionados às atividades decorrentes de manutenção. Embora exista a preocupação sobre os custos incidentes para manter a operacionalidade dos equipamentos, poucos esforços são empregados para estender esse benefício ao inventário de peças de reposição, que impactam no custo operacional da manufatura nem sempre de forma transparente.

Esse artigo propõe uma revisão dos estudos feitos com a abordagem de DT e PHM para otimização de custos de inventário, bem como avalia as lacunas existentes e oportunidades que podem ser exploradas. O restante do artigo é organizado na seguinte ordem: a seção 2 apresenta a metodologia de pesquisa utilizada para esse estudo, na seção 3 é feito uma revisão dos conceitos de DT e PHM encontrado na literatura, na seção 4 é discutido os trabalhos encontrados com aderência ao tema pesquisado e na seção 5 é concluído o estudo e apresentado propostas para trabalhos futuros.

2 Metodologia

Para conduzir o estudo, duas buscas diferentes foram feitas para encontrar o referencial teórico para o tema proposto, utilizando a base da ScienceDirect e da CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), que foi adicionada na segunda etapa. Na primeira etapa foram utilizados os seguintes termos combinados: (“digital twin” AND MRO) OR (PHM AND MRO) OR (“smart manufacturing” OR MRO) considerando a busca dos termos em todo o artigo e com data superior a 2010. Foram encontrados 45 artigos na base da ScienceDirect com termos pesquisados.

Em função do número de publicações encontradas foi feito uma busca adicional combinando todos os termos e utilizando taxonomia entre os termos principais de pesquisa, a busca foi restrita ao título, resumo e palavras-chave na base da ScienceDirect, e ao assunto na base da CAPES. Os termos utilizados na busca foram os seguintes: (“digital twin” OR “smart manufacturing” OR “industry 4.0”) AND (PHM OR prognostics OR “predictive maintenance”) AND (MRO OR “spare parts” OR maintenance). Foram encontrados 57 artigos na base da ScienceDirect e 22 na base da CAPES. Em

ambas as etapas foram considerados artigos publicados em inglês e com data de publicação superior a 2010.

Após a remoção de artigos duplicados e fora do contexto de manufatura e indústria, restaram 115, dos quais foram avaliados o conteúdo para averiguar a aderência ao tema proposto. Para considerar que o artigo possuía aderência ao tema, foi levado em consideração a abordagem de DT e ou PH com conexão direta ou indireta com o inventário de peças de reposição. Dessa forma, a citação do inventário ou custo de peças foi considerado uma aderência direta ao tema, e a predição de vida útil de componentes com foco em custo foi considerada uma forma indireta, já que essa informação pode ser usada com um dos indicadores para uma otimização de níveis de estoque. Como resultado, 34 artigos foram selecionados para a pesquisa, conforme representado (Fig. 1).

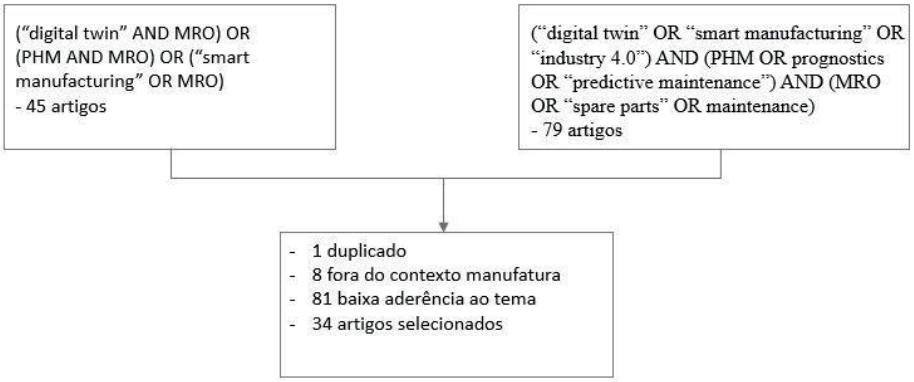

Fig. 1. – Metodologia aplicada na pesquisa

3 Tecnologias Relacionadas

3.1 Digital Twin

Apesar de serem altamente relacionados, os conceitos da tecnologia de DT surgiram antes da Indústria 4.0 em uma apresentação na faculdade de Michigan em 2002 [9] como uma proposta do conceito de PLM (Product Life Cycle), e desde então tem recebido uma expressiva atenção por pesquisadores. De uma forma geral, DT é a representação virtual de sistema ou objeto físico capaz de simular as características e comportamentos de sua contraparte física, além de ambos estarem mutualmente conectados [3]. Entre as várias definições sobre DT, [3] afirma que a mais comumente usada foi proposta em 2012 por Glaessegen e Stargel, no qual DT é composto por três partes: produtos físicos, produtos virtuais e as conexões entre eles. Contudo, uma das primeiras definições foi dado pela NASA [1], onde DT é uma simulação probabilística integrada multi-física, multi-escalável de um produto ou sistema que utiliza os melhores modelos físicos disponíveis para refletir a vida do seu correspondente gêmeo.

Apesar de DT ter uma expressiva abordagem em aplicações complexas relacionado a aeronaves, usinas geradoras de energia, aerogeradores [2] e engenharia aeroespacial [10], a atenção tem se voltado para novas aplicações na manufatura industrial como modelagem de produtos, processos e operações bem como a interoperabilidade entre eles [11]. Também é ampla a abordagem de DT em equipamentos e sistemas industriais de alta performance, tanto para processos de manufatura [1, 3, 12, 13, 14] como para manutenção preditiva [15, 16, 17, 18], mas não limitado a essas áreas de aplicação incluindo todo o ciclo de vida do produto [4].

DT utiliza dos recursos do CPS (cyber-physical systems) para implementar soluções dentro do contexto da manufatura inteligente, integrando os sistemas físicos como ativos e processos de produção, com os elementos do ambiente virtual [19] de processamento e simulação. [20] define como CPS como um ambiente onde sistemas naturais e elaborados pelo homem são fortemente integrados aos sistemas de computação, comunicação e controle. CPS é uma parte fundamental no contexto da indústria 4.0, promovendo uma conectividade avançada de dados em tempo real e uma gestão inteligente com alta capacidade analítica [21].

3.2 PHM

A manutenção preventiva tem sido uma grande aliada dos processos de manufatura, garantindo uma maior disponibilidade dos ativos produtivos com um mínimo de interrupções não programadas [22]. Embora tenha seus pontos positivos, tem um custo relativamente elevado não evita todas as falhas decorrentes de manutenção, isso porque com sua característica de inspeções ou trocas de componentes programadas por tempo (TBM) nem sempre tem sua eficácia comprovada [23]. As inspeções cobrem apenas uma parte das características necessárias para garantir o funcionamento adequado de sistemas e componentes, e a troca programada nem sempre consegue usufruir todo o potencial de uso de um componente, que por muitas vezes pode ser trocado antecipadamente gerando um custo adicional ao processo [24].

Com o avanço em tecnologias de inspeção muitas atividades de manutenção preventiva têm sido gradativamente substituídas pela manutenção preditiva ou baseada na condição (CBM), onde inspeções com auxílio de equipamentos conseguem medir a saúde do conjunto ou componente monitorado, evidenciando potenciais pontos de falhas antecipadamente [24]. Técnicas como análise de vibração, termografia e ferrografia permitem analisar o estado de um equipamento planejando intervenções programadas reduzindo o risco de interrupções durante sua operação. Contudo, muitas dessas atividades também são programadas em intervalos de tempo, além da necessidade serem analisadas por um especialista, não faz uma estimativa adequada da vida útil restante (RUL) [19].

Considerado uma evolução do CBM, o PHM (Prognostics and Health Management) faz o uso de ferramentas e algoritmos com características preditivas para previsão da vida útil restante e identificar possíveis pontos de falhas [25]. A vantagem da manutenção preditiva baseada nos fatores de saúde do equipamento, é poder trabalhar com um prognóstico precoce com indicação do que e quando ser tratado, auxiliando nas tomadas de decisões estratégicas do planejamento de manutenção [26]. Dentro do contexto de

manufatura inteligente e indústria 4.0, PHM desempenha um papel importante na manutenção preditiva, buscando manter a confiabilidade dos ativos com a correta estimativa de RUL ao longo do seu ciclo de vida [27], através da avaliação da degradação dos sistemas e componentes monitorados.

Segundo [19] o termo prognóstico e gestão de saúde, tem origem na área de medicina, mas foi adotado pela manutenção e gestão de ativos em função de sua semelhança em sua semântica, já que PHM é baseado na monitoração de sinais importantes através de sensores em pontos estratégicos e seus dados armazenado para análise. Embora PHM seja considerado um modelo de manutenção preditiva, aborda um conjunto de técnicas e métodos empregados para gerar prognósticos e suportar a gestão de manutenção [27], como monitoramento da condição em tempo real e previsão futura baseada em dados históricos e atualizados, além da estimativa de vida útil restante [8].

4 DT e PHM para Gestão de MRO e Inventário

Na literatura é possível encontrar uma ampla abordagem da aplicação de DT e PHM no contexto de manufatura e manutenção, visando o aumento de performance dos ativos e sua confiabilidade, além de propiciar uma melhor previsibilidade das ações tomadas pela gestão da manutenção. A aplicação proveniente dessas tecnologias na era da indústria 4.0, consequentemente conduz a uma redução de custos para as organizações, entretanto, nem todos os benefícios ainda estão sendo explorados. Além do suporte no planejamento das atividades de manutenção e da redução de paradas não programadas, a estimativa do RUL obtida por meio de DT e PHM, também pode beneficiar o planejamento e otimização do inventário de peças de reposição. O alto custo de muitos itens de reposição que muitas vezes são armazenados sem previsão de uso, impactam financeiramente as organizações, já que o valor do item fica imobilizado e não pode ser convertido em capital para uso, além dos custos da gestão do inventário.

Dentro da literatura utilizada nesse estudo, [28] Kumar et al. é o único a considerar diretamente o uso da manutenção preditiva e a estimativa de RUL como fator para redução do custo de inventário de materiais e peças de reposição. Mesmo quando não citado diretamente, RUL pode ser considerado um fator importante para a gestão de níveis de inventário, [29] propõe uma prova de conceito do uso de DT em máquinas com baixa disponibilidade de aquisição de dados através de aplicação de monitoramento em paralelo dos principais componentes para estimativa de RUL.

Quando a área de aplicação é a indústria, é possível observar o uso de DT e PHM em equipamentos complexos como centros de usinagem e fresadoras com comando numérico (CNC), [15] propõe um sistema de manutenção preditiva hibrida com DT baseado em modelo e orientado a dados para estimar e acompanhar a RUL dos principais componentes, [12] também apresenta um estudo com modelagem similar para previsão da condição de máquinas-ferramenta com objetivo na análise e previsão da degradação de ferramentas de corte. [23] Einabadi et al. propõe um método de manutenção preditiva dinâmica para indústria 4.0, baseado em dados em tempo real e redes neurais artificiais (ANN) para prognóstico de falhas, reduzindo intervenções desnecessárias de manutenção, explorando a vida útil de componentes o máximo possível e

reduzindo ou prevenindo paradas não programadas. Ainda no contexto de ativos complexos, Tao et al. [30] propõe uma aplicação em DT baseado em PHM para controle de ciclo de vida de turbinas aerogeradores. O estudo de caso aplicado apresentado por [30] aborda não somente as questões de eficiência, mas indiretamente os custos envolvidos em função da complexidade das atividades em função das características do equipamento. No quadro 1 é apresentado de forma resumida uma visão geral dos principais estudos relacionados ao tema.

Quadro 1 - Visão geral dos principais estudos relacionados ao tema pesquisado

Autores	Dimensão	Framework	Principais abordagens
Roy et. al (2016)	Manutenção		Análise e monitoramento de degradação de componentes elétricos e mecânicos de forma geral sob o contexto de MRO e PHM. Aborda obsolescência, manutenção autonoma e planejamento integrado.
Li et. al (2020)	Manutenção Aeronaves	x	Aborda design de projetos PHM, baseado na definição de expectativas de stakeholders
Lamoureux et. al (2014)	Manutenção Aeronaves		Validação de indicadores de PHM antes da implementação
Werner et. al (2019), Booyse et. al (2020), Nuñez et. al (2017), Susto et. al (2018), Cattaneo et. al (2019)	Manutenção		Estratégia para a implementação de manutenção preditiva em indústria com uso de DT e PHM com foco em RUL
Raman et. al (2018)	Engenharia aeroespacial		Aborda a importância de DT em MRO nos métodos de manufatura modernos
Luo et. al (2020)	Manutenção	x	Aplicação de DT orientado a dados hibridos para manutenção preditiva e estimativa de RUL
Short et. al (2019), Aivaliotis et. al (2019)	Manutenção		Aplicação de DT com modelagem para manutenção preditiva
Sénéchal et. al (2019)	Manutenção	x	Aborda CPS, prognósticos para atividades de manutenação com foco em sustentabilidade
Einabadi et. al (2019)	Manutenção		Apresenta o uso de sensoremento e redes neurais no contexto de industria 4.0 para estimativa de RUL
Traini et. al (2019), Ruiz-Sarmiento et. al (2020)	Manutenção	x	Machine learning aplicado à manutenção preditiva para redução de custos e com foco em RUL
Ardila et. al (2020)	Manutenção		Propõe um sistema de informação para PHM baseado em três pilares: Heterogeneidade, integração e usabilidade de busca
Kumar et. al (2017)	Manutenção	x	Big data aplicado à CBM para maior precisão na estimativa de RUL e redução de custo de peças de reposição
Tao et. al. (2018)	Geração de energia		Aplicação de DT orientado a PHM para ativos de alta complexidade de manutenção
Kraft et. al (2017), Liu et. al (2018)	Manutenção aeronaves		DT voltado à aplicações de MRO

Muitas pesquisas com abordagem na estimativa de RUL também são encontradas na área de manutenção de aeronaves, que além da complexidade é extremamente crítico em função segurança envolvida, sendo inclusive monitorada por autoridades reguladoras [31]. Contudo, além das expectativas diferenciadas desse tipo de atividade, é possível encontrar aplicações visando um maior controle dos itens de reposição [31, 32, 33], bem como a vida útil dos componentes em uso [32, 33, 34].

5 Conclusão

Com o advento da indústria 4.0 e as tecnologias relacionadas que impulsionam o desenvolvimento de novas técnicas e métodos para um desempenho superior e sustentável na manufatura, é possível perceber a necessidade de mudança de paradigmas e comportamentos nessa nova era industrial, onde IoT está cada vez mais presente. Muitas abordagens na literatura e na indústria já demonstram os primeiros movimentos para mudança com propostas e resultados promissores, embora, muito ainda precisa ser explorado no contexto da manufatura inteligente.

DT e PHM desempenham um papel importante quando o assunto é desempenho e previsibilidade de ativos, e esse trabalho procurou relacionar os estudos que possuem conexões com o inventário de materiais e peças de reposição para ativos utilizados na manufatura. Dentro dos resultados encontrados não foi identificado uma grande relação direta com o tema, entretanto, como a estimativa de RUL é uma preocupação em boa parte dos temas pesquisados, é correto afirmar que de forma indireta a otimização de níveis de inventário pode ser tratada.

Como trabalhos futuros é sugerido uma maior conexão entre abordagens de DT e PHM com inventário de materiais e itens de reposição, aumentando o potencial de resultados na organização estendendo a conexão na cadeia de valor do ativo. A fase de maturação das novas tecnologias ainda está no início, e há um grande potencial a ser explorado em breve.

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Hybrid method PROMETHEE-SAPEVO-M1: multicriteria evaluation of River Combat Vessels to support Amazon defense

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Abstract. There is a need for the Brazilian Navy to make investments in combat vessels for application regarding the defense operations in the Amazon region, carried out by the Marine Corps. For the decision-making analysis, the hybrid method named PROMETHEE-SAPEVO-M1 is worked, allowing an evaluation with qualitative and quantitative data, generating weights for the criteria in a structured way, and providing a robust analysis from the results by three different models of evaluation along with an intra-criterion analysis. In search to enable the implementation of the methodology to the case, a web platform based on the method is used, presenting a friendly interface, requiring only numeric entries and preference indications. The method implemented shows to be effective to the study from the moment that it makes possible a robust analysis, providing the Brazilian Navy and its Marine Corps to identify the most favorable vessel for acquisition in search of safeguarding the Amazon.

Keywords: Decision-making, Multiple Criteria Decision Analysis, PROMETHEE, Brazilian Navy.

1 Introduction

Based on the Brazilian Federal Constitution [1], the Brazilian Navy (BN) aims to prepare and employ naval power contributing to the defense of the country, guaranteeing constitutional powers and ensuring law and order, fulfilling the duties provided by the law, with emphasis on those related to the Maritime Authority, aiming to contribute to safeguarding national interests [2]. In this context, it is possible to deduce that the efficient use of its resources is essential to the BN, ensuring the protection of the national territory and, in this scenario, the Amazon region.

The Amazon region has strategic and geopolitical importance for Brazil, where its area presents 60% of the surface of Latin America, with 67.8% belonging to the country [3]. According to Andrade [4], the territory has 13,190 km of borders with other countries, and around 25,000 km of navigable areas within nine Brazilian states, which considering the connection to the Atlantic Ocean, enable the Amazon to become commercially relate to the United States, Europe, and Asia.

Not Considering only political aspects, in the Amazon region, it is necessary to focus attention on the recurrent threats related to terrorism, drug trafficking, guerrilla, and paramilitary groups [5]. According to the Brazilian Defense Strategy, in search to counter threats to the Amazon, it is crucial to carry out a series of strategic actions related to the military presence to defend natural wealth. Regarding the BN, it is necessary to provide naval, aircraft, and Marine Corps (MC) assets in a permanent condition of employment, especially on the waterways of the main rivers in the Amazon region [6].

Currently, the BN has military organizations from the MC located in the Amazon region, sustaining a relatively small number of troops when compared to the challenge of safeguarding the Amazon, and has been presenting low investments regarding vehicles of river fighting [4]. The current vessels used are practically destined for the transport of troops but presenting a set of limitations, such as low firepower, low autonomy, absence of armored protection, and other aspects.

Considering the hypothesis of possible investment in modern river fighting vessels, in search of the increase of effectiveness in strategic actions and contemplating limited resources, a decision-making analysis process is necessary, enabling to identify which alternative, among those available for employment, is favorable for acquisition. In search to make possible an adequate realization of this procedure, a set of criteria and variables must be analyzed [5].

Contemplating an analysis composed by the set of criteria and the trade-off presented between them, the implementation of Multiple Criteria Decision Analysis (MCDA) methods would provide to BN and its MC a robust analysis regarding the decision-making process, by the moment that these methods enable the structuring and a better understanding of preferences regarding the problematic [7].

The MCDA methods can be understood as techniques that support and enable the decision-maker, being an individual agent, group, or organization, to structure and evaluate complex problems transparently, introducing quantitative and qualitative criteria [8], where the criteria preference is defined in an interactive process with other technical-political actors [9]. As presented by Greco et al. [10], the MCDA methods allow the analysis of a decision-making process, considering various aspects of evaluation,

such as technical, environmental, and socioeconomic, at operational and strategic scenarios for decision-making.

Considering a real decision-making problem, the method to be implemented should enable an integrated algorithm, providing to perform qualitative and quantitative data, facilitating to structure and analyze variables where it is not possible to define a precise numerical input along with variables in a quantitative format [11]. Consider aspects of subjectivity in the MCDA modeling is an important role [12], transcribing the preferences of the decision-maker by the implemented method, being clear concerning the manipulations and attributions regarding the problem in evaluation.

1.1 Questions and Objectives

The paper aims to present a case study based on the MCDA methodology through the hybrid method PROMETHEE-SAPEVO-M1 [13] by the moment that its axiomatic structure enables the evaluation of both qualitative and quantitative data, in an integrated way, correlated to the problematic. Considering the hypothetical situation of acquiring new combat vessels the study aims to provide to the BN a procedure for decision-making analysis in search to obtain a ranking of the vehicles and identify the most favorable between them.

Enabling an effective application of the method to the case study, a web platform [14] based on the modeling will be worked, supporting the data evaluation in the given case, providing an assertive analysis by its friendly interface and complete format of results presentation by numerical and graphical models.

After the paper introduction, section 2 presents the concepts of the PROMETHEE-SAPEVO-M1 method and its axiomatic structure. Section 3 exposes the implementation process of the modeling in the case study intended for the multicriteria evaluation based on the analysis of combat vessels for use Amazon operations. Section 4 concludes the work, presenting the gains of the new method and proposal for future studies.

2 PROMETHEE-SAPEVO-M1 method

The method is a new variant of the PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluations), proposed by Brans, Vincke, and Mareschal [15], where a structure based in cardinal inputs, were added technics of ordinal evaluation based on the concepts of SAPEVO-M method, an extension of SAPEVO method [16], representing the integration of two MCDA methods.

The PROMETHEE-SAPEVO-M1 method enables the evaluation of data in different natures, where the qualitative and quantitative procedures are performed by ordinal and cardinal entries, respectively. Another main point of the modeling is its weights set for criteria, provided by a pairwise comparison to transparently obtaining of the importance as the subjective view of the decision-maker.

The modeling provides three models of analysis as partial outranking, complete outranking, and a ranking by intervals. Also, it is provided an intra-criterion analysis by veto threshold, enabling the evaluation of the alternative performance in a specific criterion. This format of results analysis enables decision-makers to make a sensitivity

analysis of the case by the comparison between the results suggestions in each preference model.

2.1 Evaluation procedure

The evaluation process is structured into a matrix (Criterion x Alternative) (1), composed of a set of alternatives A, where $a_i \in A$, $i = 1, \ldots, n$, evaluated under a set of qualitative criteria h, $h = 1, \ldots L$, and a set of quantitative criteria j, $j = 1, \ldots k$.

	a_1	a_2	a_3	...	a_n
h_1	a_{11}	a_{21}	a_{31}	...	a_{n1}
h_L	a_{1L}	a_{2L}	a_{3L}	...	a_{nL}
j_1	a_{11}	a_{21}	a_{31}	...	a_{n1}
j_k	a_{1k}	a_{2k}	a_{3k}	...	a_{nK}

(1)

Considering the presence of qualitative and quantitative criteria, first, the set A is performed concerning qualitative criteria h, $h = 1, \ldots L$. Considering a pairwise comparison between the alternatives regarding each criterion from set h, the analysis is based on the preference evaluation present on an importance scale, table 1.

Table 1. Importance scale.

Absolutely worse	**-3**
Much worse	**-2**
Worst	**-1**
Equivalent	**0**
Best	**1**
Much better	**2**
Absolutely better	**3**

For each qualitative criterion evaluated, it is obtained a matrix of preference relation between the elements belonging to the set A. By the equation (2), the punctuation is normalized, obtaining an importance degree of each alternative in a specific criterion. Then the values are submitted toa maximization procedure $P_h(a_1, a_2) = P(d) = f(a_1) - f(a_2)$, enabling to obtain the difference between the alternatives, as works the PROMETHEE method. The qualitative evaluation finishes making the normalization of difference by the equation (3).

$$v = \frac{\sum a_{ih} - \min a_{ih}}{max\ a_{ih} - \min a_{ih}} \tag{2}$$

$$P(d) = \begin{cases} d/1 & d \leq 1 \\ 1 & d > 1 \end{cases} \tag{3}$$

The evaluation process regarding the quantitative criteria j, $j = 1, \ldots k$, it is sustained the cardinal format based on the PROMETHEE procedure.

Comparing the alternatives a_1 and a_2 from set A, $P_j(a_1, a_2) = P(d)$ represents the preference degree of a_1 over a_2 according to the criterion j. When the criterion needs to be maximized, uses $P(d) = f(a_1) - f(a_2)$ to define a preference function. If it is necessary to minimize the criterion, $P(d) = f(a_2) - f(a_1)$ is used as preference function.

Six types of preference function have been proposed to normalize the differences between the alternatives [17], where based in parameters of indifference and preference, it is possible to obtain linear and strict preference, for more detail of application, please consult [18].

After the evaluation of alternatives, it is necessary to obtain the criteria weights. Considering both qualitative and quantitative criteria only in one set j, $j = 1, ..., L + k$, the ordinal scale presented in the table 1 is used, where the preference relation between the criteria is performed.

In this evaluation, two variables called *maximum sum* and *minimum sum* is considered, enable the normalization of punctuation (4). The *maximum sum* is obtained by $x = (n-1).\ 3$, representing the highest possible preference punctuating sum of each criterion, as closer a criterion is to *maximum sum*, greater will be its dominance in the set. In other hands, *minimum sum* is obtained by $x = (n-1).\ -3$, representing the minimum value possible within that assessment, as lower be the value and its closer to the *minimum sum*, the criterion will represent a little importance in the set.

$$\upsilon = \frac{\sum c_{ij} - (max\ sum)}{(max\ sum) - (min\ sum)} \tag{4}$$

After the normalization, each degree will be submitted to equation (5), providing the weights according to their respective criteria, and enabling to generate the global index preference $\pi\ (a_1, a_2)$, indicating the preference degree of alternative a_1 over a_2, where (6):

$$w(c_j) = \frac{\upsilon(c_j)}{\sum \upsilon(c_j)} \tag{5}$$

$$\pi(a_1, a_2) = \sum_{j=1}^{k+l} P_j(a_1, a_2) w_j \tag{6}$$

2.2 Results analysis model

Finished the aggregation procedure, the results are analyzed in different formats of manipulation, by a partial and complete outranking, and an outranking by intervals.

The Partial outranking is handles with by the positive outranking flow (7) and negative outranking flow (8), representing how a_1 outranks the other alternatives and how a_1 is outranked by the other options. How higher be the positive flow and lower be the negative flow, more favorable will be the alternative, where (9) (10) (11):

$$\phi^+(a_1) = \frac{1}{n-1}\sum_{x \in A} \pi(a_1, x) \tag{7}$$

$$\phi^-(a_1) = \frac{1}{n-1}\sum_{x \in A} \pi(x, a_1) \tag{8}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\begin{cases} \phi^+(a_1) > \phi^+(a_2)\ and\ \phi^-(a_1) < \phi^-(a_2), or \\ \phi^+(a_1) = \phi^+(a_2)\ and\ \phi^-(a_1) < \phi^-(a_2), or \\ \phi^+(a_1) > \phi^+(a_2)\ and\ \phi^-(a_1) = \phi^-(a_2); \end{cases}$ (9)

- a_1 is indifferent to a_2 ($a_1 I a_2$) *if* $\phi^+(a_1) = \phi^+(a_2)\ and\ \phi^-(a_1) = \phi^-(a_2);$ (10)

- a_1 is incompatible to a_2 ($a_1 R a_2$) *if* $\begin{cases} \phi^+(a_1) > \phi^+(a_2)\ and\ \phi^-(a_1) > \phi^-(a_2), or \\ \phi^+(a_1) < \phi^+(a_2)\ and\ \phi^-(a_1) < \phi^-(a_2); \end{cases}$ (11)

The Complete outranking is based in the net outranking flow (12), in this case, how higher be the net flow, more favorable is the alternative, where (13) (14):

$$\phi(a_1) = \phi^+ a_1 - \phi^- a_1 \tag{12}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\phi(a_1) > \phi(a_2)$ (13)

- a_1 is indifferent to a_2 ($a_1 I a_2$) *if* $\phi(a_1) = \phi(a_2)$ (14)

The third model of evaluation, consisting in an interval procedure [$x(a_1)$, $y(a_1)$] (15), based in a standard error value, defining a complete outranking by intervals, where (16) (17):

$$\begin{cases} x_{a_1} = \phi(a_1) - \alpha\sigma_{a_1} \\ y_{a_1} = \phi(a_1) + \alpha\sigma_{a_1} \end{cases} \tag{15}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\phi(a_1) > \phi(a_2)$ (16)

- a_1 is indifferent to a_2 ($a_1 I a_2$) *if* $\phi(a_1) = \phi(a_2)$ (17)

In search to obtain a robust analysis of the decision-making problem, the intra-criterion analysis by veto threshold suggests an equivalence between alternatives with low performance (a_x) and high performance (a_y) in global analysis, from the moment that a_x presents a strict preference over a_y in a specific criterion cj.

The veto v_j does not influence the outranking flows, but the analysis works as additional information to the decision-making process, where $v_j \geq p_j \geq q_j$. For qualitative criteria $v_h = 1$, and for quantitative criteria $v_j = max(a_{ij})$. If a preference threshold (p_j) be set and it is greater than v_j, the veto becomes equivalent to preference $v_j = p_j$.

3 Case study

In search to obtain an effective proposal to assist the defense of the Amazon region, the case study will address the allocation of resources assertively for the acquisition of River Combat Vessels. The analysis is evaluated concerning four vessels, as exposed in figure 1, to rank them according to their respective criteria. The decision-making process will be worked by the PROMETHEE-SAPEVO-M1 method, along with its web platform.

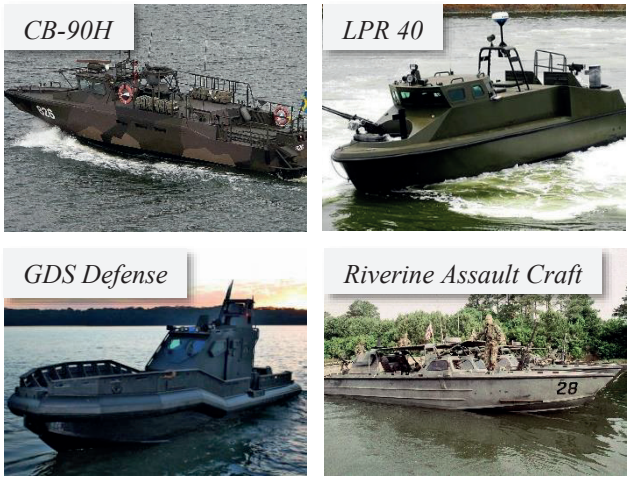

Fig. 1. River Combat Vessels to analysis.

Based on information acquired through specialists of MC, being them officers with experience in real operations in riverside environments, a set of ten criteria was defined, being five for a qualitative and five for quantitative assessment. The criteria were classified as the variables with the greatest operational importance, performing several operations in the Amazon region. The criteria are detailed below:

- *Fighting Power:* Important requirement for operations, when considering the occupation of points on the rivers and carry out river blocks, the criterion will be evaluated qualitatively, considering the set of armament that composes each vessel;
- *Navigation System*: Criterion characterized by the set of equipment as radar, GPS, and echo sounder, evaluated qualitatively;
- *Protection System*: Characterized by the shielding system that makes up the vessel, performed qualitatively;
- *Cost*: Criterion of great importance, however, evaluated qualitatively, due to the need for secrecy regarding the respective values of each vessel;

- *Maintenance*: Qualitative criterion regarding maintenance difficulties in isolated regions and the need for specific training, along with their costs;
- *Maximum Speed*: Criterion that considers the need for fast occupation at critical points in the rivers, measured in nautical knots;
- *Cruising Speed*: The criterion is related to the maximum time of working regarding the best performance of the vessel, measured by nautical knots.
- *Autonomy*: Considering long hours operations and the difficulty of supply points in the rivers of the Amazon, the autonomy indicates the ability to operate without the need for refueling, evaluated by nautical miles;
- *Displacement Weight*: Criterion characterized by the maximum capacity for loading troops and equipment destined for operations, measured by tons;
- *Troop Capacity*: Required when the number of troops is related to the combat power, measured by the number of combatants per vessel.

With the data for analysis, table 2 exposes the evaluation matrix, composed of qualitative, presenting a subjective indication of preference, and quantitative criteria, related to the numerical performance of each alternative.

Table 2. Evaluation matrix of case study.

Criteria	*CB-90H*	*LPR 40*	*Riverine Assault Craft*	*GDS Defense*
Fighting Power	Very good	Good	Good	Good
Navigation System	Very good	Very good	Fair	Good
Protection System	Very good	Very good	Good	Fair
Cost	High	Medium	Medium	Low
Maintenance	High	High	Fair	Good
Maximum Speed (knots)	45	35	50	35
Cruising Speed (knots)	37	28	38	28
Autonomy (Nautical miles)	300	270	280	270
Displacement Weight (T)	18	12.5	7.5	1.7
Troop Capacity (Qty)	20	16	10	10

3.1 Method application and result analysis

By the web platform, it is necessary to register the data related to the structure problem regarding the number of alternatives and criteria and their names. The software process follows the same axiomatic structure of the method, first evaluating the alternatives regarding the qualitative criteria. Indicating the preference between the pairs based on the ordinal scale (table 1), as exemplified in figure 2, it is possible to obtain the matrices

of relation, exposing the preference degree between each pair of alternatives in each criterion.

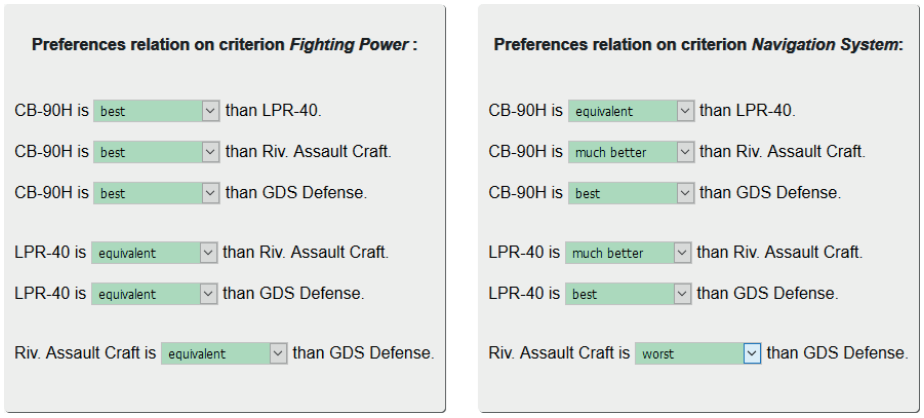

Fig. 2. Evaluation of vessels under qualitative criteria, PROMETHEE-SAPEVO-M1 Software web.

Regarding the quantitative evaluation set (figure 3), it is necessary to indicate the numerical performance of each alternative in each criterion, defining if it is a process of maximization or minimization. The type of preference function to the normalization process is the main topic of the analysis procedure, where is considered two models for evaluation.

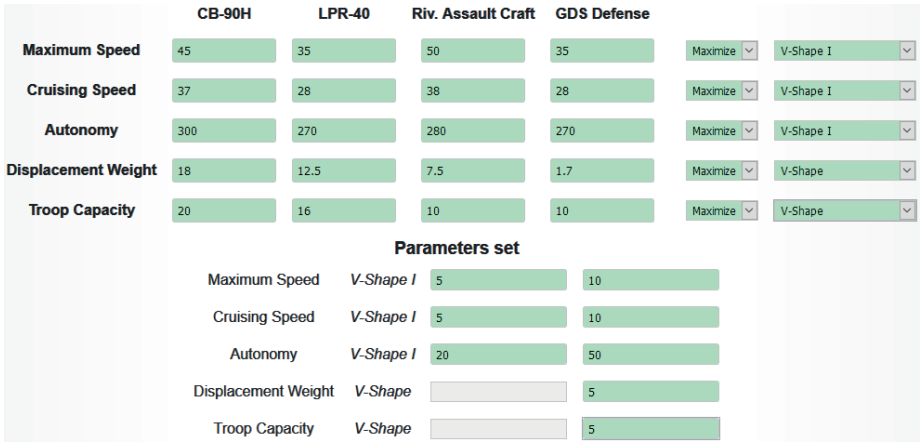

Fig. 3. Evaluation of vessels under quantitative criteria, PROMETHEE-SAPEVO-M1 Software web.

To evaluate the Maximum Speed, Cruising Speed, and Autonomy, it was considered the V-shape I function, by the moment that the function considers a limit of indifference q, where all differences under this limit will not indicate any preference, and the limit of strict preference p, where all value upper than this threshold will present the maximum preference degree, remembering that all differences between the limits p and q

presents a linear preference. For normalization of the differences in *Displacement Weight* and *Troop Capacity*, is set the preference function *V-shape*, defining only a strict preference threshold, by the moment that these criteria are sensible and a minimum variation between two alternatives need to take into account. Figure 3 exposes the threshold values in detail.

After the evaluation of alternatives, the procedure follows comparing the criteria in search to obtain the preference relation and the weight respective to each one, as presented in table 3. In the software, the process is similar to qualitative evaluation, just indicating the preference relation between each criterion. In table 3 is presented the punctuation of each criterion along with the final weights obtained based on the variables of *maximum sum* and *minimum sum*.

Table 3. Matrix of importance relation and weights obtained.

maximum sum = 27

minimum sum = -27

	Fighting Power	*Navigation System*	*Protection System*	*Cost*	*Maintenance*	*Maximum Speed*	*Cruising Speed*	*Autonomy*	*Displac. Weight*	*Troop Capacity*		Punctuation		Final Weights
Fighting Power	0	3	1	1	2	3	3	2	3	2	=	20	=	0,174
Navigation System	-3	0	-2	-1	1	1	1	1	3	2	=	3	=	0,111
Protection System	-1	2	0	1	2	2	2	1	3	2	=	14	=	0,152
Cost	-1	1	-1	0	1	2	2	1	2	1	=	8	=	0,130
Maintenance	-2	-1	-2	-1	0	1	1	0	1	0	=	-3	=	0,089
Maximum Speed	-3	-1	-2	-2	-1	0	-1	-3	1	-2	=	-14	=	0,048
Cruising Speed	-3	-1	-2	-2	-1	1	0	-2	2	-1	=	-9	=	0,067
Autonomy	-2	-1	-1	-1	0	3	2	0	1	3	=	4	=	0,115
Displacement Weight	-3	-3	-3	-2	-1	-1	-2	-1	0	-3	=	-19	=	0,030
Troop Capacity	-2	-2	-2	-1	0	2	1	-3	3	0	=	-4	=	0,085

Once established the weights of each criterion, the preference degree obtained from qualitative and quantitative evaluations are weighted. Then, for each pair of alternatives is generated the global preference index, representing the degree of dominance of each vessel over the others in the set, as presented in figure 4. Through these indexes, it is possible to define the positive and negative flows, indicating how the alternative outranks and how it was outranked regarding the other, respectively, and the net flows, representing the difference between the previous flows and as higher be this punctuation, more favorable becomes the alternative.

	CB-90H	LPR-40	Riv. Assault Craft	GDS Defense	Positive Flows	Net Flows	Intervals (standard error = 0.041)	
CB-90H	0	0.041	0.048	0.064	0.153	0.118	x = 0.077	y = 0.159
LPR-40	0.004	0	0.03	0.032	0.066	-0.009	x = -0.05	y = 0.032
Riv. Assault Craft	0.009	0.016	0	0.022	0.047	-0.05	x = -0.091	y = -0.009
GDS Defense	0.022	0.018	0.019	0	0.059	-0.059	x = -0.1	y = -0.018
Negative Flows	0.035	0.075	0.097	0.118				

Fig. 4. Global index of preference between each pair of alternatives, along with the positive, negative and net outranking, PROMETHEE-SAPEVO-M1 Software web.

The PROMETHEE-SAPEVO-M1 method enables three models of results analysis, based on a partial, complete, and intervals outranking. A graphical representation of each model of preference analysis provides the evaluation of all alternatives performance.

In figure 5, the preference relationships between the vessels assessed are detailed by a chart regarding the partial outranking. It observed that the alternative of better performance was the vessel *CB-90H*, presenting the highest positive and the lowest negative flow, indicating a total preference within the evaluation. The *LPR-40* vessel registered a partial preference regarding the alternatives *Riverine Assault Craft* and *GDS Defense*, where these alternatives presented an incompatible relation between each other, by the parallel indication in the chart.

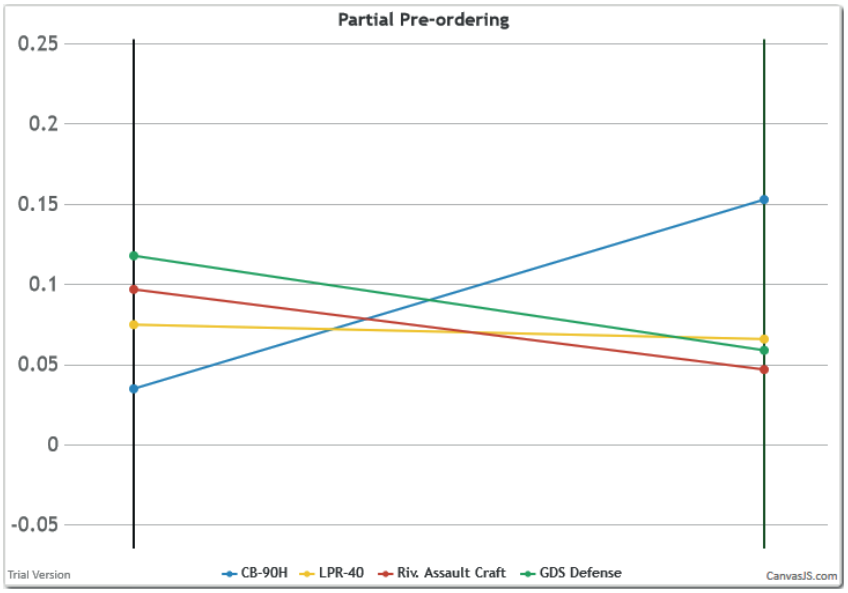

Fig. 5. Partial outranking chart, PROMETHEE-SAPEVO-M1 Software web.

In the second analysis, is obtained the complete outranking by the net outranking flows, related to the difference between the positive and negative flow of each alternative. In this evaluation model, how greater be the net flow obtained, most favorable becomes the alternative. In the given case, the vessel with the best performance was the *CB-90H*,

preceded by the *LPR-40*, *Riverine Assault Craft*, and *GDS Defense*, respectively, as exposed in figure 6.

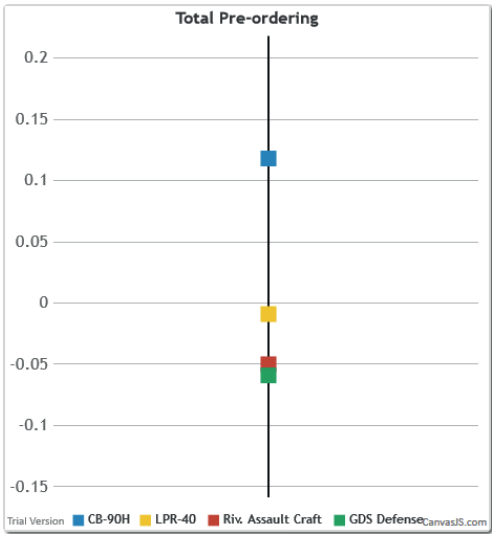

Fig. 6. Complete outranking chart, PROMETHEE-SAPEVO-M1 Software web.

The last model of analysis, outranking by intervals, enabled by the standard error, indicates if a given alternative is relatively superior concerning another or if the difference between the preferences is so small that both can become equivalent.

In the case study, the standard error value obtained was 0.041 (figure 4), so it was possible to generate the lower and upper limits for each alternative. In this assessment, both *Riverine Assault Craft* and *GDS Defense* vessels continued to present no preference regarding the others in the set, and the *CB-90H* vessel keeps presenting strict preference in the context, as detailed in figure 7.

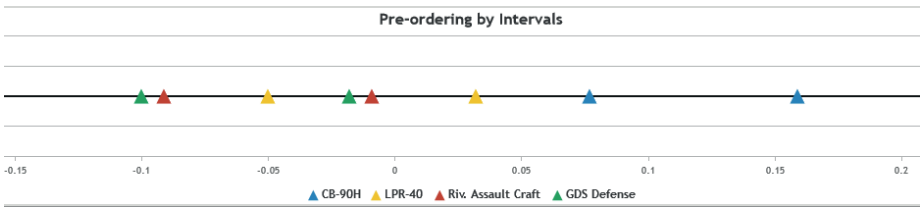

Fig. 7. Outranking by intervals chart, PROMETHEE-SAPEVO-M1 Software web.

Even already identified the best alternative, a distillation process was carried out in search to provide a second favorable alternative, by the moment that the exclusion of some alternative can present influence in the final ranking. In this context, was excluded the alternative *CB-90H*, and obtained new outranking flows. As exposed in figure 8, the alternative *LPR 40* continued to indicate the best performance concerning its positive, negative, and net flows. An important observed point is related to the outranking by intervals, where, unlike the previous analysis, the alternative presented total preference regarding the other from the set.

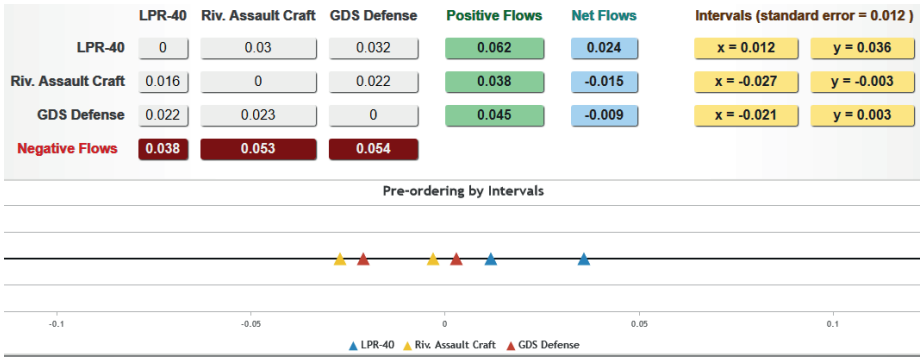

Fig. 8. New outranking flows, after distillation process along with the interval analysis charts, PROMETHEE-SAPEVO-M1 Software web.

Concerning the intra-criterion analysis, was not observed any relative relation that could present some influence or change in the choice of the most favorable alternative.

4 Conclusion

The proposed study aimed to present a decision-making process, through the application of MCDA concepts, considering the hypothesis regarding the acquisition of River Fighting Vessels by the BN for application in the riverside operations by MC in the regions of the Amazon.

The PROMETHEE-SAPEVO-M1 method proved to be efficient and effective, from the moment that it made possible a decision analysis composed of multiple criteria, being these of both quantitative and qualitative nature, and presenting an integrated format of results analysis based in three different models. The modeling also showed its robustness in terms of obtaining the weights, presenting a structured and transparent manner, making it possible to identify the criteria of most influence regarding the evaluation of the vessels.

The computational platform applied was of great help for the implementation of the algorithm in the given case, being necessary for the decision-maker to only make the inputs regarding the quantitative data and indicate the importance among the alternatives in the specific criteria. The tool also showed its potential by delivering both the results through numerical and graphical representation, bringing a better visual analysis and identifying the alternative of higher performance in the evaluation.

This work supports the military organizations within the hypothesis of identifying the acquisition of vessels as an effective way of assistance in defense operations in the Amazon region. In future studies, the BN and MC can perform a new evaluation, adding more criteria in search to obtain a more robust assessment and identifying among the possible vessels, which alternative will be more favorable for the acquisition and obtaining the intended efficiency in the Amazon operations.

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Analysis of Packaging Losses in Cocoa Butter Production

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Abstract. Manufacturing companies seek to achieve product quality combined with waste reduction in the various activities they perform. Thus, the objective of this work was to detect through Quality Tools causes that result in defects in cocoa butter fill activity. The sequence of the steps performed in this research occurred through data collection that covered a period of three months and then information was extracted and analyzed with the aid of tools such as: Check sheet, Cause and Effect Diagram, Pareto Diagram, Control Letters (Letter P), 5 whys and 5W2H. Finally, an action plan was proposed to eliminate the root cause of the identified problems, and for the actions that were implemented, the impact of the same was verified. The results of the actions focused on reducing the occurrences of defects in packaging, and the decrease in the waste of this material is evident. Thus, it was possible to observe the importance of a system for product quality is within expected standards avoiding process losses.

Keywords: Process Improvement, Quality Tools, Cocoa Butter.

1 Introduction

According to the National Association of Cocoa Processing Industries (AIPC, 2020), the average Brazilian cocoa grind for the past three years was 219,498 tons. However, this does not yet reach the installed capacity, which is 275,000 tons. In Brazil, this segment is composed of three large companies, responsible for 97% of the cocoa milling (AIPC, 2020). As it is a commodity, these companies need to guarantee the quality of products, processes and services, in addition to seeking to reduce costs to increase profit margins.

In this context, one of the alternatives for companies in the cocoa milling business to improve their production performance, is the use of managerial techniques, which enable an improvement in the operational performance of their processes.

Thus, this work aims to study the impact of using quality tools, such as Verification Sheet, Cause and Effect Diagram, Pareto Diagram, Control Letters (Letter P), 5 whys and 5W1H, for reduction of waste in a cocoa milling company, resulting from the cocoa butter filling process.

Quality tools are extremely important in the analysis of the conditions of the processes that can influence product quality, employee productivity and financial performance, as found in the survey carried out in more than 100 industrial companies by Brkic et al (2012).
The elimination of losses related to butter packaging results in the economy of resources destined to the process, which can promote reinvestments in the company (new equipment, increased efficiency, artificial intelligence, among others) to improve the speed and volume of the production.

2 Literature review

The term quality is often associated with the level of perfection or the ability to realize a project exactly according to the plan, in this perspective, Paladini (2007) declares that this concept involves several elements with perspectives of innumerable levels of importance and that it is not recommended to strategically focus efforts in just one or disregard any, thus weakening the company in question.
From the point of view of Toledo et al (2014), companies that benefit from the use of statistical tools obtain higher quality and productivity by minimizing the cause of the problems faced. Whether basic or of higher levels, such techniques enable the identification and prioritization of problems, achieving better results than unstructured analytical processes.
Montgomery (2004) points out that there is a need to teach tools to companies in general, so that they can achieve the resolution of statistical problems in the process and thereby achieve the minimization or elimination of losses and, consequently, identifying opportunities and improvements to the process.
For Daychoum (2012), the verification sheets are defined as tables or spreadsheets that aim to facilitate the collection and analysis of data, allowing a visualization mainly of their behavior patterns. Toledo et al (2014) states that from the Pareto Diagram or Analysis it is possible to verify the most relevant aspects to be prioritized over a certain unwanted event that needs to be resolved. And in this way, it allows to dedicate greater efforts and act initially, in the factors that will bring better and more noticeable results.
The control charts allow you to display the statistical control of a given process and the monitoring of its control items according to the location and its dispersion (Werkema 2013). From the point of view of Montgomery (2004), control charts have two general classifications, which are: control charts by variables and control charts by attributes. Still according to the author, this second classification is usual in situations where the quality characteristics do not allow to be quantified or measured on a continuous scale, in this way, conforming or non-conforming products, the existence or absence of attributes or quantify defects in products.
Attribute control charts can be classified into two main types, portrayed by Costa, Epprecht and Carpinetti (2013) as follows:
1. Graphics for the non-conforming fraction (p): they are used to monitor processes that manufacture a certain number of defective items even in cases where special

causes do not occur. From the data collected, according to Montgomery (2004), the control limits calculated are determined considering the standard deviation of the variables as shown in equations (1), (2) and (3). They behave according to the variation of the results due to uncontrolled causes in the process.

$$LSC = \underline{p} + 3\sqrt{\frac{\underline{p}(1-\underline{p})}{n}} \quad (1)$$

$$LC = \underline{p} \quad (2)$$

$$LIC = \underline{p} - 3\sqrt{\frac{\underline{p}(1-\underline{p})}{n}} \quad (3)$$

LSC = upper control limit;
$\overline{p}$ = general mean of the variable;
and LIC = lower control limit.

2. Graphics for number of non-conformities (c): for this model, the graphs are constructed in such a way that the occurrence of non-conformities in samples of constant size follows the Poisson distribution and for that, a large number is required potential opportunities or locations for non-conformities and that the likelihood of a non-compliance occurring in any of these locations is reduced.
The cause and effect diagram, also known as the Ishikawa diagram or "fishbone diagram", according to Simanová (2015), allows the survey and exposure of factors that directly or indirectly influence the investigated process, and can be used in almost all areas of human activity. Mahto and Kumar (2008) complement that the causes must be distributed among six categories entitled as man, machine, environment, materials, management and measures.
The 5 whys tool, for Slack, Chambers and Johnston (2002), is a technique that performs, through the simple questioning "why", the analysis of a given problem considering how it occurred. In Chaves' perspective (2000), this tool contributes to more in-depth analyzes, and for any problem there are numerous questions that determine the 5 whys.
Finally, the 5W2H is a checklist that, according to Oliveira and Tsan Hu (2018), ensures that all perspectives of a problem under study can be addressed. The acronym comes from English words that are: what, who, where, when, why, how and how much.

3 Methodology

To achieve the proposed objective, an action research was carried out in a cocoa processing industry, located in the south of Bahia. Through the chosen method, it was possible to analyze a problem situation, and from the researcher's intervention, verify the change in the behavior of the process, after the interventions performed. The study started with a bibliographic search, with the purpose of forming the theoretical framework that guided the data collection. Data collection covered a period of three months. Observations were carried out from June to August 2019 in which defects in

the cocoa butter filling process were identified. For this purpose, check sheets of the Defect Location Checklist were used to quantify the frequency of occurrences.
The collections were made at the company's inspection area, where the products were destined for storage, at the end of the manufacturing steps. These data were collected twice to scale the problem studied and to visualize the behavior of each sample during this period. From the data collected, a Pareto chart was constructed, which helped in separating special causes from common causes. The collected data were tabulated, and then the Defective Fraction Control Chart (Chart P) was drawn up, which shows the behavior of the 35 samples collected. In which each of these represents 1 pallet with 40 products, that is, there were 35 samples of n = 40. After carrying out the analysis of the causes and carrying out the actions established to solve the main problems, Letter P, of the same structure, was applied again, with the intention of verifying if the variability of the process was reduced, and if the special causes had been eliminated. After prioritizing the defects, using the Pareto diagram, it was possible to use the cause and effect diagram tool to identify the root cause of the problems. This stage counted on the participation of the team responsible for the production of cocoa butter, in an open meeting, it was possible to list the contributing causes for the defects selected as a priority. Subsequently, the 5 (five) whys tool was used in order to determine the symptoms of the problems, showing in more depth what is really causing the irregularity and establishing a countermeasure to reduce the chances of recurrence. For this stage, a meeting was held again with the team of engineers responsible for the process and the gathered information were confirmed by the operation responsible for the sector. Finally, the countermeasures defined with the aid of the previous tool were mapped and activities were carried out to achieve them. For this, the 5W1H tool was used to outline what would be done, who would do what, in what time interval, where it would be applied and all the reasons why the activities should be done.

4 Results

The research was carried out in a multinational cocoa processing factory located in the southern region of Bahia. With an average of 250 direct employees, the company serves the chocolate and cosmetics market in the sale of products such as liquor, powder and cocoa butter. The study kept the focus on the final stages of the butter manufacturing process, illustrated in figure 4, being more specific between the filling sector and the cold chambers, the stage studied does not have automated machinery.

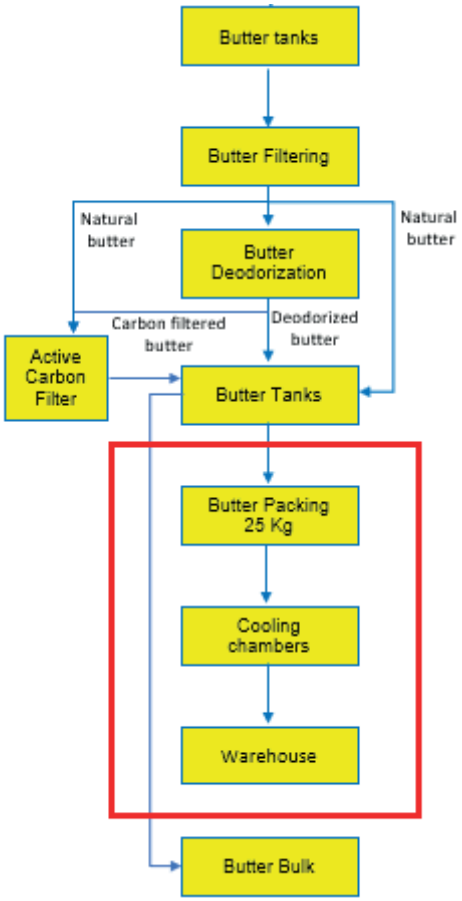

Figure 4. Cocoa butter process after extraction.

From the data collected from the process, a non-conforming fraction graph (p) was constructed, as can be seen in figure 5, and when analyzing the process data, it was found the presence of special causes and high variability in the process -button of butter, which reflects among other things in the cost of this process, since according to Montgomery (2004), the variability of the process directly influences the manufacturing cost.

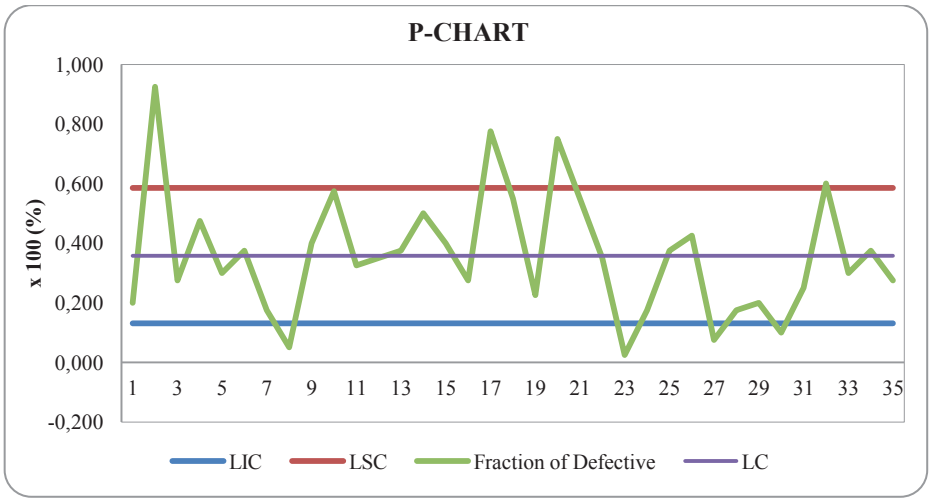

Figure 5. Control chart p of the first collection of defects in packaging (survey data).

The control chart p considered the presence of a defect in a box, that is, it has a defect or not, and only by analyzing this graph it was not possible to identify what the defect was. Thus, in order to verify the main types of defects in the boxes, a pareto chart - figure 6 was elaborated, in which it is possible to observe that the defects "dirty box" and "bulged box represented 90% of the problems, for this reason were chosen to be the object of this study.

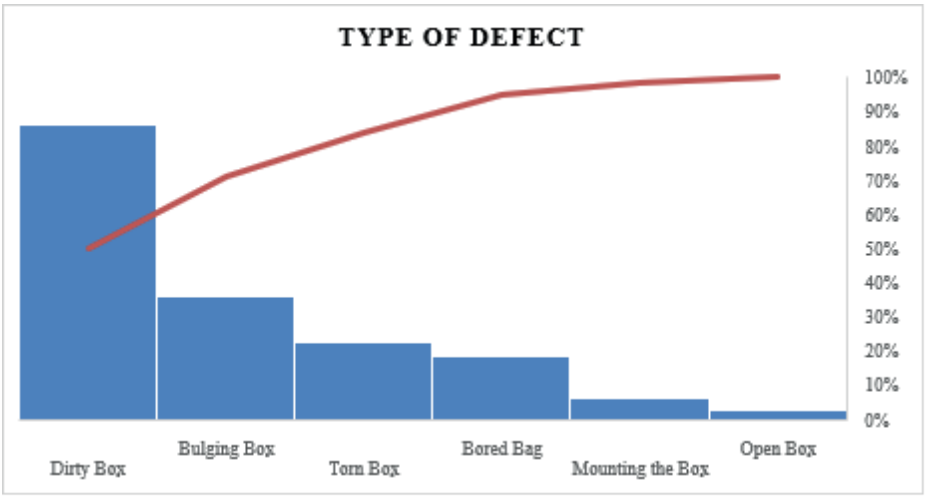

Figure 6. Pareto diagram on types of defects in butter packaging (survey data).

To identify the factors that cause the defects: dirty box and curved box, the Ishikawa Diagram, figures 7 and 8 were used. From the analysis of the result of these diagrams,

it was observed that there were causes that resulted in both defects, as for example the inefficiency of butter tempering. For this reason, these were prioritized since, at first, their resolution should result in the reduction of both problems with the same actions.

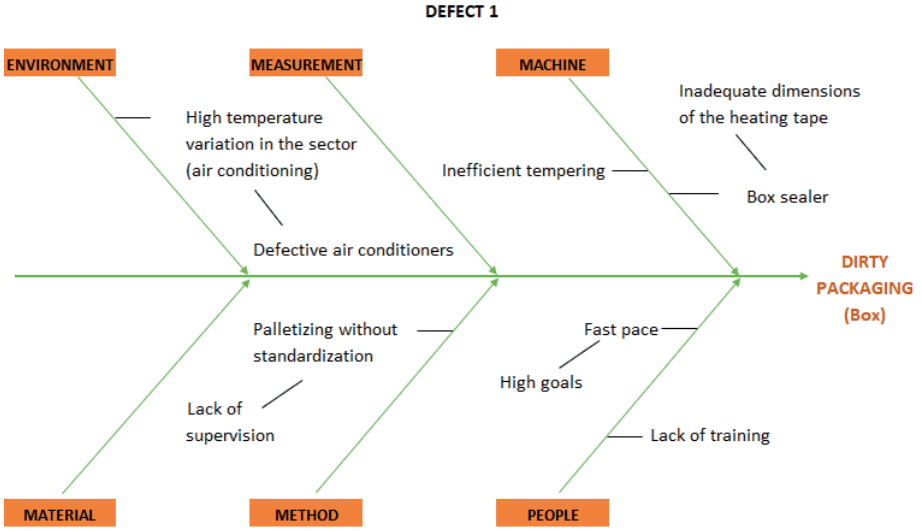

Figure 7. Ishikawa diagram for the defect "Dirty Packaging (Box)" (survey data).

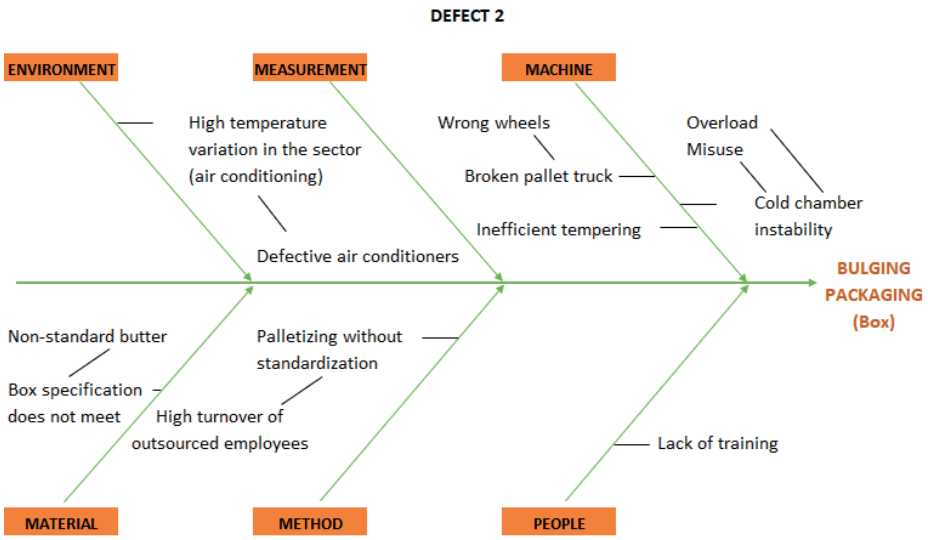

Figure 8. Ishikawa diagram for the defect "Bulk Packing (Box)" (survey data).

After defining the potential causes for the two problems, a structured action plan was drawn up based on the 5W1 H quality tool. For this, all the actions carried out and those that were not carried out were raised, as can be seen in Annex 1. After the im-

plementation of the actions, a new data collection was carried out, in August 2019, to verify their efficiency. A new attribute control chart was built, shown in figure 9.

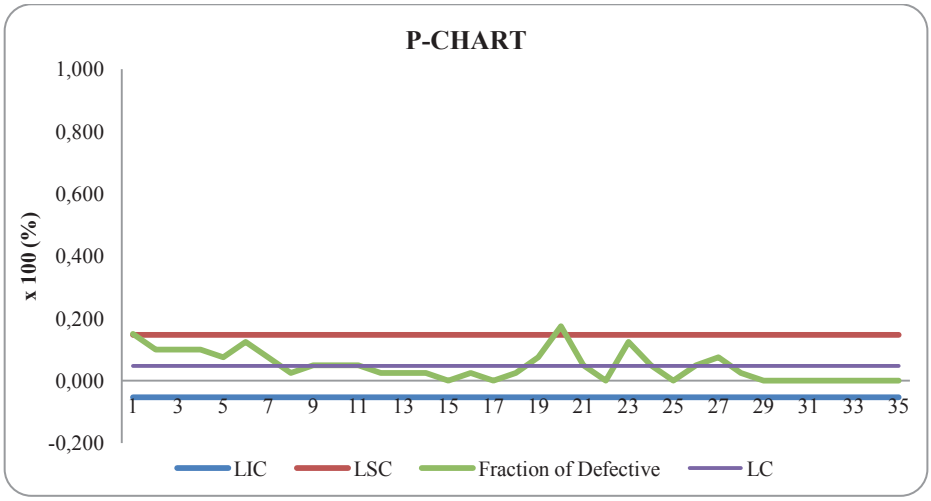

Figure 9. Control chart p for the second collection of defects in packaging (survey data).

As can be seen, there was a reduction in the variability of the process after the application of the actions and with that, the narrowing between the control limits becomes noticeable once the standard deviation has decreased. Although the process showed an improvement, there were still the appearance of special causes due to the defects that were not treated in this research.

The effect of the actions was reflected in the decrease of the number of defects and, consequently, in the reduction of the number of packages that were used in excess in the process of reworking the final product, becoming evident the impact on the waste of this material. An improvement can be seen by differentiating the number of boxes used in the production of the product from those that were stored in the physical packaging condition. In Figure 10, it is possible to check the quantity of boxes wasted in each period for an average of approximately 700 tons produced/month.

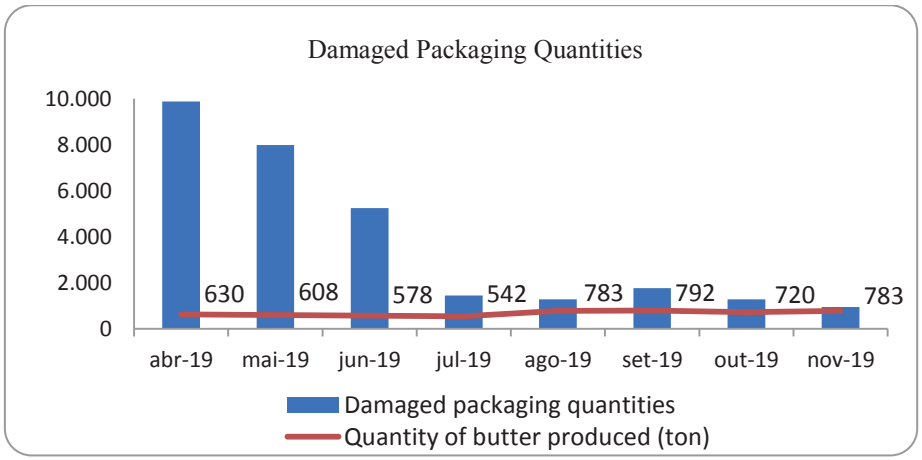

Figure 10. Number of boxes wasted in the company per month (survey data).

The number of damaged boxes was 9875 units before the study was carried out. After the application of certain actions discussed, there was a drop to an average of 1443 wasted boxes, which demonstrates how significant the measures taken were, reflecting directly on the cost of the product, since each box costs $ 0.41.

5 Discussions and conclusions

The purpose of this work was to identify which factors interfere in the filling stage and cause defects in cocoa butter packaging in the filling and inspection sector of a company in southern Bahia. This objective was achieved through the use of Statistical Process Control (CEP) and Quality Tools in the construction of the study.

In this study, it was possible to notice that the filling operation was out of control when detecting special causes in the letter P, referring to the first collection. After carrying out some of the established actions, such as changing the seasoning and the refrigeration system, repairing pallet trucks and others, there were still special causes, showing that this process still has some deficiencies, reflecting the non-elimination of all the root causes of the process, since not all the proposed actions have been carried out.

It is noted that there was a reduction in the causes that led to the occurrence of defects in the filling process, this can be seen in the decrease of this event by approximately 90% when comparing the results from the months of April to November of the year 2019, as shown previously. As a result, the company benefited both in reducing its own costs and also in reducing reprocessing, avoiding excess costs and inconveniences during the manufacturing process.

The use of statistical techniques requires continuous learning combined with knowledge of the process and the effort to implement them, enabling the obtainment of results that contribute to the success of the business. The recurrence of the causes

of quality variability is due to differences or inconsistency in several factors and the control of these causes can be achieved through training, raw material control, preventive maintenance, standard operating procedures and among others.
According to the work developed by Erginel et. al (2011), control charts were used to evaluate data and verify the stability of the cookie packaging process in a food industry in Turkey, which could conclude the existence of a stable process.
The Charter of Control was a fundamental tool, which effectively made it possible to understand and substantiate the decision making that was reflected in course adjustment actions. Such a tool associated with others, seen previously, have shown good results proving the applicability of this type of study to the work of the cocoa processing industry.

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Diretrizes para projetos de IIoT em contexto CPS

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Abstract. A transformação digital é um requisito chave para o futuro das organizações, porém, promovê-la é uma tarefa complexa. Neste contexto temos IIoT (*industrial internet of things*) como habilitador para criação de CPS (*cyber physical systems*) e DT (*digital twin*). Este artigo busca na literatura exemplos de arquiteturas, frameworks e estudos de caso referentes a IIoT e compara estas referências a uma pesquisa de campo de implementação de CBM (*condition based maintenance*) em uma máquina CNC. Visto que o número de artigos referente a implementação de IIoT em cenários *brownfield* ainda é pequeno tanto na academia como no meio profissional, este artigo propõe fornecer um mapa orientativo para auxiliar na condução de projetos piloto de IIoT neste cenário. Observa-se uma forte demanda na manufatura para aplicação dos conceitos e tecnologias de IIoT de forma modular e incremental, sendo estes determinantes para o desenvolvimento de maturidade em relação aos requisitos da indústria 4.0.

Keywords: CBM, IIoT, CPS, DT, Brownfield.

Abstract. Digital transformation is a key requirement for the future of organizations, however, promoting it is a complex task. In this context, we have IIoT (industrial internet of things) as the enabler for creating CPS (cyber-physical systems) and DT (digital twin). This paper searches the literature for examples of architectures, frameworks, and IIoT case studies and compares these references with field research regarding CBM implementation (condition-based maintenance) on a CNC machine. Since the number of articles referring to the implementation of IIoT in brownfield scenarios is still small, both in academia and in the professional environment, this paper proposes to provide a guide map to assist in the conduct of IIoT pilot projects in the brownfield scenario. There is a strong demand for manufacturing for the application of IIoT concepts and technologies in a modular and incremental way, and it could be determinants for the development of maturity concerning the requirements of industry 4.0.

Keywords: CBM, IIoT, CPS, DT, Brownfield.

1 Introdução

Originalmente utilizado na Alemanha no ano de 2011 o termo 4ª revolução industrial ou Indústria 4.0 (I4.0) teve como premissa aumentar a produtividade, flexibilidade, interconexão e segurança na cadeia produtiva alemã [1]. No artigo [2] relata-se que em 2013 foi organizado o primeiro grupo de pesquisa para I4.0 onde elaborou-se recomendações iniciais para implementação, sendo elencado três componentes chaves: IoT, CPS e *Smart factory*. Boyes et. al [1] ainda afirma que a *Industrial Internet of Things* (IIoT) é meio pelo qual os objetos no chão de fábrica estabeleçam uma interconexão em uma rede até plataformas computacionais, permitindo habilitar acesso, coleta, análise de dados para tomada de decisões e controle em tempo real.

Em termos de cenários para implementação de IIoT este artigo caracteriza-se pela aplicação em ambiente *brownfield* [3], este termo faz referência a aplicações em instalações já existentes. Este artigo foca no cenário *brownfield*, visto que esta é uma característica de grande parte da manufatura no Brasil. Tem-se como válido, nesta situação, tentar equacionar as mudanças demandadas pela transformação digital às características já existentes na manufatura, como estruturas de *hardware* e *software*, modelos de gestão, cultura organizacional e viabilidade em termos de custo.

No que tange ao contexto de implementações de IIoT, observam-se dificuldades desde a definição de requisitos para infraestrutura de hardware e software escaláveis e adaptáveis ao legado de máquinas, como a falta de convergência da Tecnologia da Automação (TA) e a Tecnologia da Informação (TI), além dos custo para implementação e a justificativa técnica dos projetos [4]. Neste contexto, o artigo tem como objetivo utilizar as referências acadêmicas e iniciativas industriais relacionadas à IIoT, somadas às observações de uma pesquisa de campo como fundamentação para elencar pontos que norteiem projetos pilotos de IIoT. Diante destas considerações apresenta-se a questão problema: Como as organizações poderiam se preparar para implementação de projetos pilotos de IIoT? Para tratar desta problemática o artigo está organizado em 5 seções. Na seção 2 é descrita a metodologia de pesquisa utilizada. Na seção 3 apresenta a revisão da literatura em relação a frameworks e trabalhos de implementação de IIoT na manufatura. Já na seção 4, apresenta-se um mapa orientativo resultante das informações da literatura e observações da pesquisa de campo com foco na implementação de IIoT para CBM em uma máquina CNC. Encerrando o artigo, na seção 5, apresentam-se as considerações finais.

2 Metodologia de Pesquisa

Uma pesquisa bibliográfica foi executada nas plataformas Science Direct, IEEE e Springer, a seleção dos artigos foi executada em duas etapas, pesquisando-se, na primeira etapa, por títulos através da composição dos termos conforme Figura 2. Em segunda etapa foi avaliado o tópico resumo, priorizando artigos com aderência a orientação para aplicação ou estudo de implementação de IIoT em chão de fábrica.

Em acréscimo à revisão da literatura, uma pesquisa de campo foi conduzida de forma a amparar o desenvolvimento de um mapa orientativo, caracterizando assim como uma

pesquisa aplicada, descritiva e de campo. Ilustra-se na Figura 1 a delimitação da pesquisa de campo (linha pontilhada), onde avalia-se a implementação de um sistema IIoT para aquisição de dados de componentes de máquinas, habilitando-se desta forma o primeiro nível da arquitetura 5C de CPS denominado CBM. Ainda na Figura 1 representando o conteúdo de pesquisa deste artigo, somam-se a IIoT e CBM os níveis PHM, CPS da arquitetura 5C e o DT, todos estes tendo como habilitador da interconexão entre camada física e virtual a IIoT.

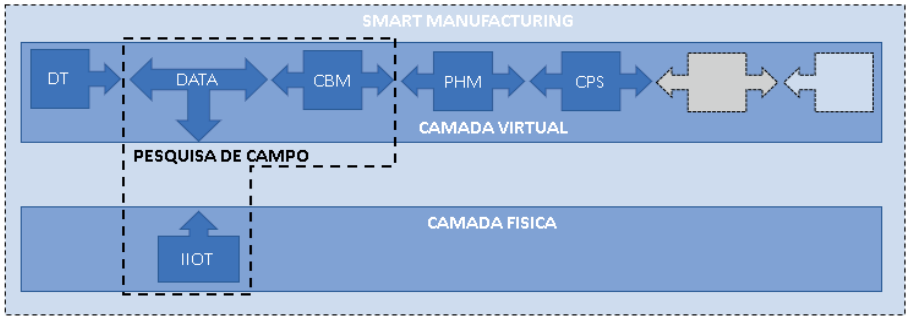

Fig. 1. Principais elementos da pesquisa bibliográfica e de campo (Fonte: Autor)

Destaca-se que o referencial teórico a ser utilizado na construção do mapa orientativo da seção 4 será formado de elementos identificados nos artigos obtidos da pesquisa relativos aos grupos 1, 2 e 3 conforme ilustra Figura 2. Já os elementos identificados nos artigos do grupo 4 serão utilizados para contextualização em relação as técnicas associadas às camadas 1 e 2 da arquitetura 5C de CPS, orientação esta, devido a correlação ao projeto da pesquisa de campo realizado.

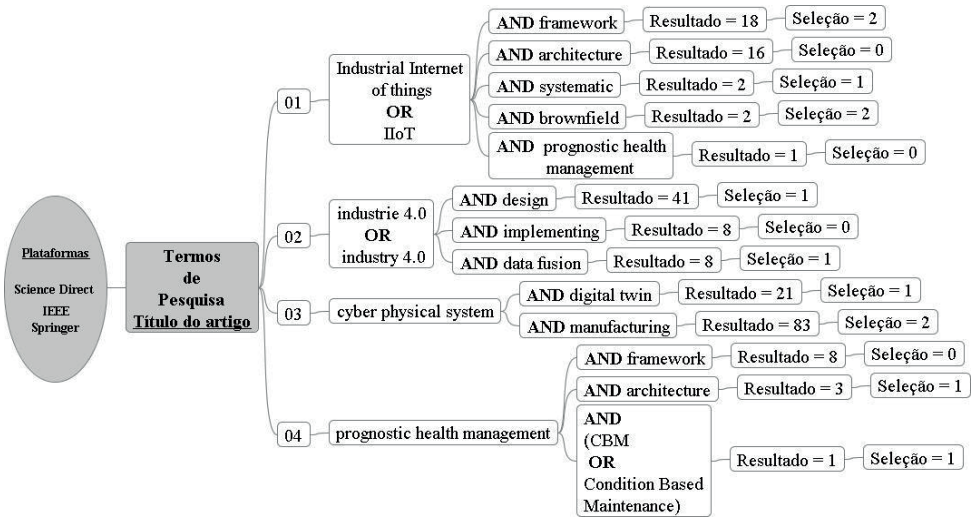

Fig. 2. Composição de termos da pesquisa bibliográfica (Fonte: Autor)

Levantam-se três hipóteses em relação aos aspectos internos do cenário observado que podem dificultar a implementação de projetos de IIoT: (H1) falta de conhecimento estruturado no tocante ao nível de implementação de IIoT; (H2) falta de priorização de projetos de IIoT devido a não comprovação da relação custo e benefício; (H3) falta sinergia entre indústria e academia para pesquisa, desenvolvimento, aplicação e validação de conceitos.

3 Revisão da Literatura

Relacionado ao escopo da IIoT, conforme artigo [2] caracterizam-se alguns princípios da I4.0 como: interconexão, transparência da informação, decisões descentralizadas e assistência técnica. Observando os princípios listados e o cenário Brasil em termos técnicos, ou seja, introdução de novas tecnologias em infraestruturas já existentes, qualificação profissional, matriz de ensino, modelos de gestão, metodologias de trabalho e fatores sócio econômicos, observa-se potenciais oportunidades bem como desafios [4]. Estes se apresentam sob conceitos associados como *Cyber Physical System* (CPS), *Digital Twin* (DT) e *Prognostics and Health Management* (PHM) que definem conceitualmente escopos de iniciativas e aplicações IIoT.

3.1 Iniciativas e Trabalhos Relacionados a IIoT – Pontos Chaves da Bibliografia Selecionada

Os autores [1] apresentam uma revisão da literatura sobre hierarquias para sistemas IIoT e elaboração de um framework. O framework visa orientar a implementação de IIoT, propondo uma infraestrutura dividida em seis categorias principais e suas respectivas subcategorias. Para exemplificar listam-se as seis principais: (i) Setores da indústria, (ii) localização do dispositivo, (iii) Conectividade, (iv) Características funcionais do dispositivo, (v) tecnologia do dispositivo e (vi) usuário.

Já em [4] , os autores apresentam como resultado da revisão da literatura e entrevista com especialistas da área de IIoT, uma proposta de framework, dividido em três categorias principais e sub categorias, conforme segue: (i) Arquitetura de IIoT - subdivide-se em hardware, software, segurança e comunicação, (ii) Implementação - subdivide-se em pré implementação, implementação e pós implementação, (iii) Conhecimento - subdivide-se vantagens, desafios, treinamento e reconhecimento.

No artigo [3] é investigado aplicações de baixo custo de IIoT em cenário brownfield. As principais contribuições identificadas foram a abordagem de custo para projetos, um comparativo entre sete modelos de arquiteturas de IIoT em relação a seis requisitos: (i) ciclo vida do produto, (ii) segurança de dados, (iii) neutralidade, (iv) detalhamento a nível teórico, (v) implementação orientada a nível de detalhe e (vi) recomendações para implementação. Um fato interessante é que apenas a arquitetura *Azure IoT* recebe classificação satisfatória em relação aos requisitos (v) e (vi).

Ainda no artigo [3] apresenta-se um estudo de caso utilizando o framework da metodologia CRISP-DM (*Cross Industry Standard Process for Data Mining*), processo

este divido nas fases de compreensão do negócio, compreensão dos dados, preparação dos dados, modelamento, avaliação e desdobramento.

Sob a ótica de dados e informação, no artigo [5], é apresentado um mapeamento de conceitos, modelos, arquiteturas e frameworks referente a aplicação de *data fusion* na I4.0, e este é definido como uma questão estratégica para processamento dos dados coletados de várias fontes no chão de fábrica. Em termos de definição o autor cita *data fusion* como um processo automático ou semiautomáticos de autodetecção, associação, correlação, estimação de dados e informação de múltiplos canais incluindo as bases do IIoT.

Os autores [6] apresentam uma revisão sistemática da literatura delimitada por quatro questões envolvendo: (i) atores, áreas e local de aplicação, (ii) padrões e tecnologias de comunicação para IIoT, (iii) áreas de IIoT com mais esforços de pesquisas e (iv) principais implementações de IIoT. Do resultado das quatro questões destacam-se: (i) 79,6% dos artigos tem origem em universidades e em maioria concentrados na Europa, Ásia e América do Norte.

Sobre a questão (ii) apresenta-se um estudo comparativo entre o número de artigos que elencam padrões de comunicação versus as camadas de comunicação de rede (*Modelo OSI - Open System Interconnection*) que estes padrões pertencem, (iii) sumariza os esforços de pesquisa em relação as três perspectivas do modelo RAMI 4.0, ressaltando-se a falta de pesquisa sobre as camadas produto, ativo e integração, e finalizando, (iv) é apresentado percentual de artigos de IIoT e I4.0 versus objetivos de desenvolvimento, destaca-se os 3 menores percentuais referente IIoT – pois estes seriam elementares para a aplicação prática de IIoT, estes são organização do trabalho e projeto, treinamento e contínuo desenvolvimento profissional e padrões regulatórios, conforme Figura 3.

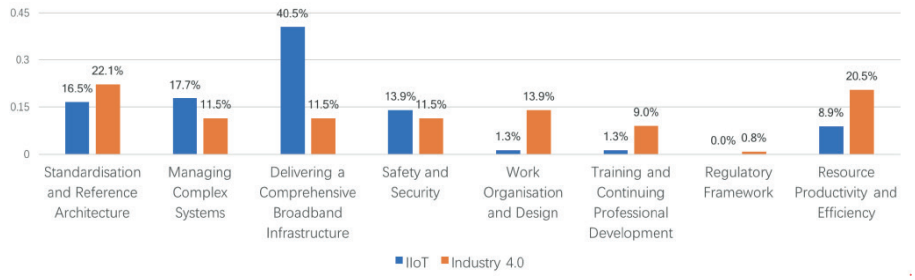

Fig. 3. Comparação entre IIoT e I4.0 e oito áreas de ações prioritárias (Fonte: [6])

3.2 Áreas Correlatas a IIoT – Cyber Physical System (CPS) e Digital Twin (DT), Prognostics and Health Management (PHM)

A contextualização do tema IIoT se ampara em três conceitos com bastante evidência atual – CPS, DT e PHM. Inicia-se com uma breve descrição dos mesmos e na sequência destacam-se as principais contribuições com base em artigos selecionados.

Os CPS's são caracterizados pela integração de sistemas físicos com redes de comunicação e sistemas computacionais onde operações são monitoradas, controladas e

coordenadas. Como exemplo de aplicação tem-se carros autônomos, robôs cirurgiões, fábricas inteligentes entre outros. A arquitetura de CPS é dividida em 5 camadas (5C): conexão inteligente, conversão de dados, cyber, cognição e configuração, [7].

O Digital Twin (DT) também é resultado da integração preconizada pelo CPS, entretanto, tem como objetivo produzir uma versão virtual idêntica ao mundo físico, replicando características físicas, comportamentais e geométricas. O DT tem foco em usar as informações coletadas em tempo real e dados históricos para, por exemplo, desenvolver produtos, modelar e simular cenários, gestão de ciclo de vida de produtos, entre outros. Apesar da similaridade entre o CPS e DT, o CPS tem uma abordagem mais no poder de computação e comunicação com o mundo físico com foco no controle e tomadas de decisão autônomas no processo; já o DT possui uma abordagem relacionada ao uso de modelos matemáticos para simulação e virtualização [8].

Os autores do artigo [7] apresentam o CPS para manufatura no conceito de *Cyber Physical Production System* (CPPS), destacando-se no trabalho uma pesquisa bibliográfica abrangente, uma tabela de convergência entre tecnologias do mundo virtual e físico (tecnologia da informação e automação) e a apresentação da arquitetura 5C demonstrando sequência de implementação de um sistema CPPS. Um compilado de dez estudos de caso de implementação do nível de sensor a rede de produção e cadeia de suprimento é ainda apresentado.

Em [9] apresenta-se as definições e técnicas associadas da arquitetura 5C para CPS em seus cinco níveis na sequência hierárquica de implementação, (i) *smart connection*, (ii) *data information convertion*, (iii) *Cyber*, (iv) *cognition*, (v) *configuration*. Os autores também apresentam um guia de implementação de CPS. Destaca-se que com esta infraestrutura implementada, este sistema permite registro, troca, rastreabilidade, comparação e a adição de conhecimento baseados nos dados monitorados dos elementos conectados à rede via interfaces e algoritmos utilizados no CPS. Outra questão relevante é a abordagem para análise de dados para CPS nomeada "*time machine*".

Sobre "*time machine*" apresenta-s em três seções paralelas, (i) *snapshot machine* para gerenciar a ocupação de espaço e o poder de processamento o armazenamento é executado somente quando ocorre mudanças significativas da máquina ou componente monitorados, (ii) *similarity identification* com o volume de dados das diversas máquina gera-se a probabilidade de identificar padrões de falha em menor intervalo de tempo com a comparação de comportamento de máquinas similares, segundo autores é possível empregar algoritmos de modo a aumentar precisão da predição do estado futuro do sistema monitorado.

E em (iii), apresenta-se *synthesis optimized future steps*, a predição de vida útil remanescente auxilia a estratégia de manutenção além de garantir uso ótimo do ativo. Padrões históricos de máquinas similares em seus estágios de utilização são também úteis para simulações de possíveis cenários de uso futuro. Concluindo [9] elenca-se vantagens de CPS categorizada em três níveis, (i) nível componentes críticos, estes monitorados via sensores provendo dados e convertidos em informação em tempo real, habilitando-se um gêmeo digital do componente que em etapas subsequentes podem favorecer a predição e auto cognição.

Em segundo (ii) a nível máquina como um conjunto de componentes monitorados tornando-se possível criar o gêmeo digital de cada máquina e por fim (iii) a nível de

sistemas de produção com conhecimento agregado de máquinas e componentes monitorados e interconectados, atribui-se características de auto comparação, autoconfiguração e auto manutenção.

Alinhado com a pesquisa de campo sobre IIoT para aplicação em CBM há o conceito da técnica de *Prognostics and Health Management* (PHM), visto que a primeira camada do CPS está relacionada a conexão e ações para monitoramento da condição (CBM) e a camada posterior de conversão com aplicação de PHM para auto reconhecimento. O conceito PHM refere-se ao monitoramento do estado de saúde de componentes de máquina, sendo o processo divido em duas funções - uma de diagnóstico onde a falha é identificada e isolada, e outra de prognóstico onde o modelo é atualizado, determinando-se a vida útil remanescente e ações de correção [10].

Em termos práticos a diferença principal entre CBM e PHM está no processamento e resultados obtidos ao aplicar os métodos; em relação ao consumo de dados as fontes são similares, com coleta dados em tempo real e históricos de componentes, máquinas, processos. No CBM grandezas são monitorados e quando estes atingem os limites pré-estabelecidos é feito diagnóstico e a especificação de ações corretivas,[11]. Já o PHM utiliza-se de modelos matemáticos para, além de identificar e isolar a falha, prever vida útil remanescente do componente e ainda faz uso dos dados para atualizar o modelo matemático [10]

Em [10] o PHM é apresentado em termos de desafios, necessidades, métodos e melhores práticas. Os desafios e necessidades foram agrupados em relação aos tópicos: etapas do PHM (diagnóstico e prognóstico), arquitetura e componentes, negócio e fatores humanos. Sobre os métodos de PHM, cita-se a análise baseada na experiência humana, modelos estatísticos e os híbridos. Em relação as melhores práticas são avaliadas PHM com base nas categorias: avaliação do custo benefício e confiabilidade, requisitos e gestão de dados, técnicas de medição, etapas diagnóstica e prognóstica, teste e o treinamento.

No artigo [12], os autores citam que não há uma definição consistente em termos de arquitetura para PHM, apresentando uma sistemática metodológica para definição de arquitetura de forma a abranger todo ciclo de vida do produto. Como resultado, propõe uma arquitetura genérica que representa o processo macro de PHM na seguinte ordem: aquisição de dados, processamento de dados, avaliação diagnóstica de falha, avaliação prognóstica e gerenciamento da saúde. Adicionalmente esta arquitetura é aplicada em um estudo de caso com o propósito de validação.

4 Iniciativa de Implementação de CBM – Mapa Orientativo

O objeto de estudo é um centro de usinagem CNC, ano de fabricação 1999 que integra uma linha de usinagem em uma indústria do setor automotivo. A arquitetura base da unidade de comando é composta de um CNC da família Siemens 840D com CLP incorporado da série S7 300 da Siemens, tendo-se a troca de sinais nível máquina via ligação ponto a ponto (sem rede). O projeto teve como escopo a implementação de CBM em treze pontos críticos da máquina, distribuídos para o monitoramento das grandezas de vibração, nível e temperatura de óleo hidráulico, consumo do sistema

pneumático, consumo de energia elétrica, temperatura de mancal de rolamento e temperatura do painel elétrico principal. Sumarizando as informações do projeto, apresenta-se o mapa da Figura 4 dividindo as informações levantadas em grupos: contexto, problemas e dificuldades, lições aprendidas e oportunidades.

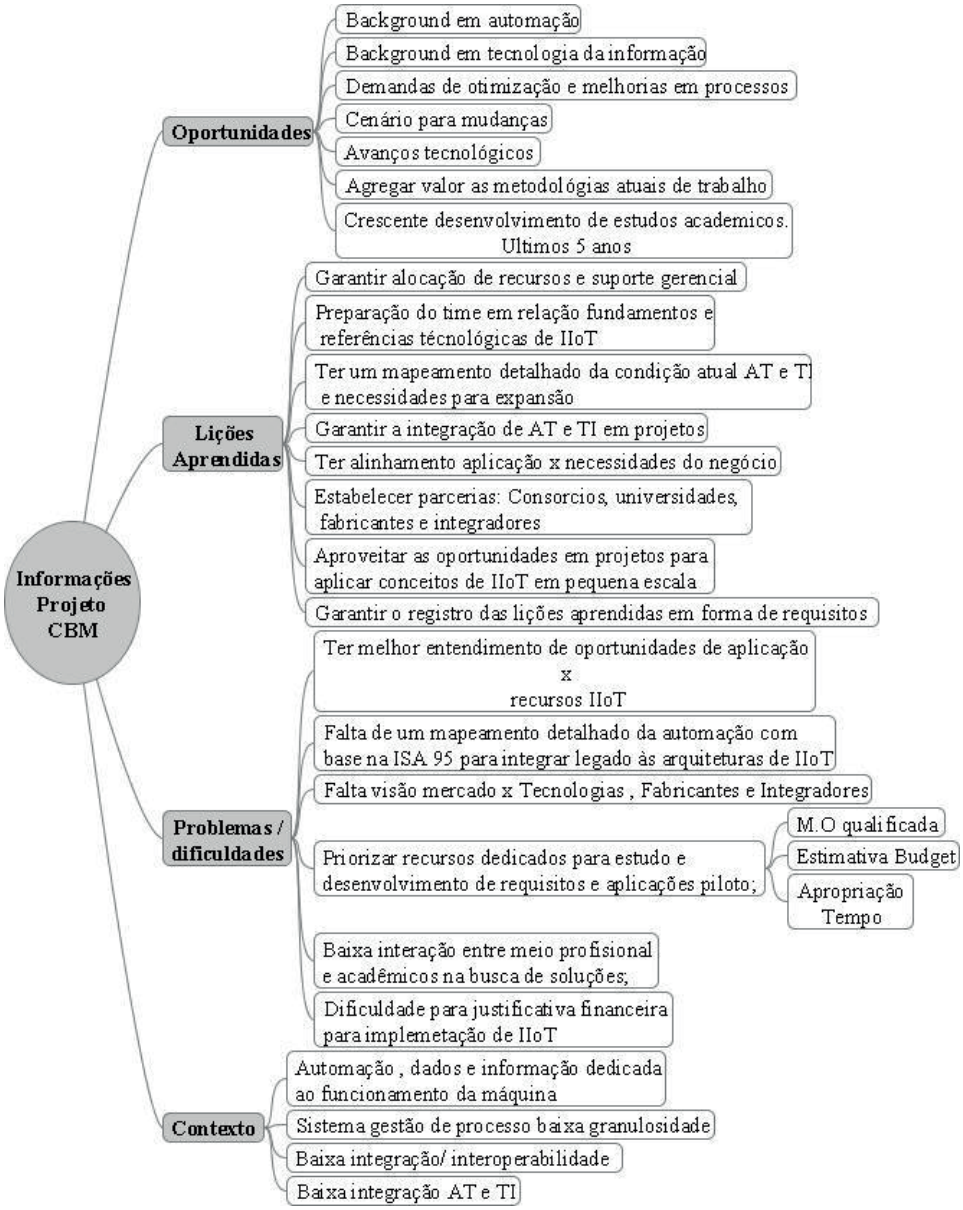

Fig. 4. Informações elencadas das observações do projeto (Fonte: Autor)

Tais informações da pesquisa de campo foram elencadas pelas observações de um dos autores que fez parte do time de implementação do projeto. Com base no compilado de informações do projeto e na revisão da literatura dos grupos 1,2 e 3 da Figura 2, foi elaborado o mapa orientativo da Figura 5 e 6 relacionando os pontos relevantes dos frameworks de IIoT e a arquitetura 5C de CPS. O mapa da figura 5 utiliza-se de insights e parte do framework [4] relacionando as etapas de pré implementação, implementação e pós implementação, bem como a arquitetura 5C de CPS apresentada em [9] e cinco categorias principais do framework de IIoT do artigo [1].

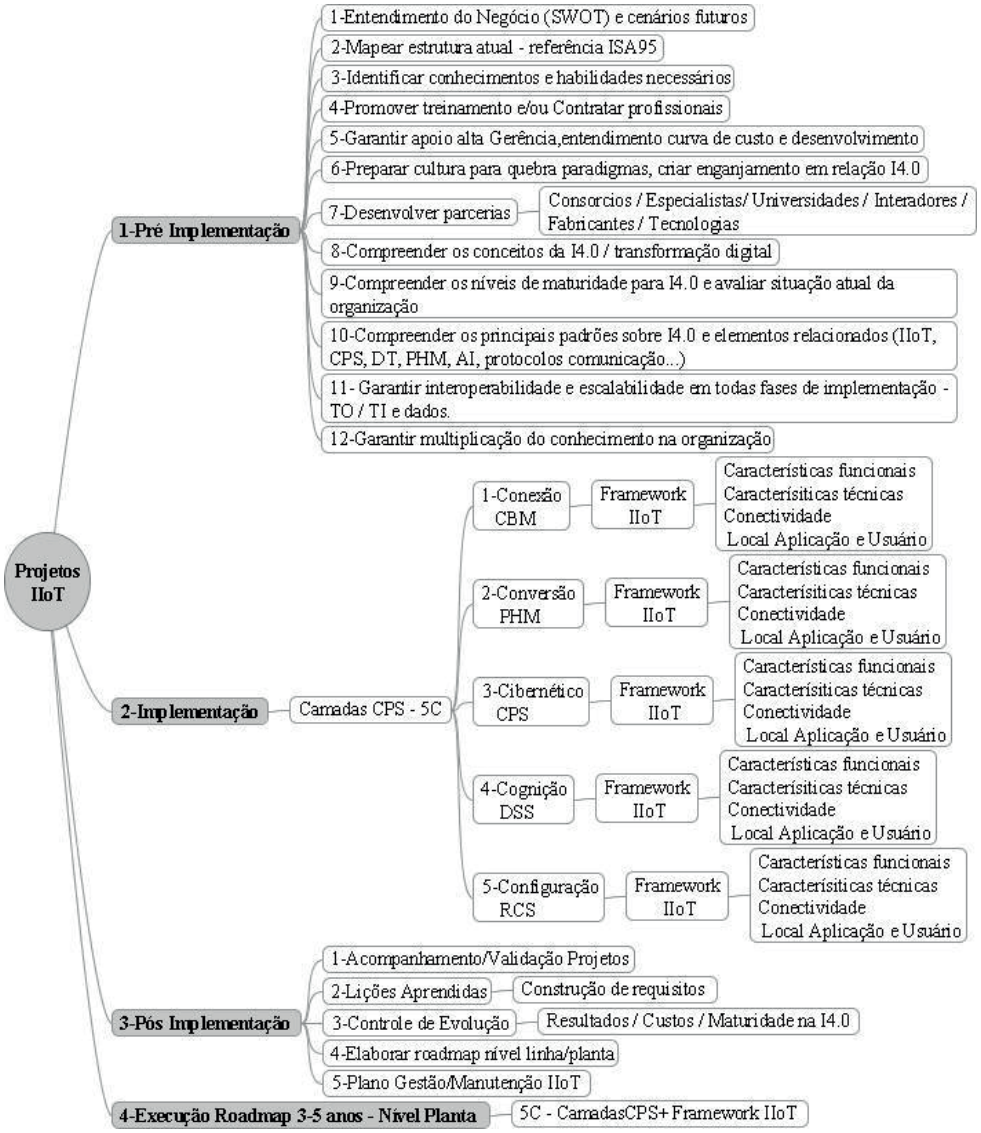

Fig. 5. Mapa orientativo para implementação projetos IIoT (Fonte: Adaptado de [1], [4], [9])

Na figura 6, apresenta-se o mapa unificando as seis categorias principais e o primeiro nível de subcategorias do framework proposto em [1] para detalhamento do componente framework de IIoT na etapa de implementação da Figura 5. Estas Figuras (5 e 6) visam dar suporte à condução de projetos piloto de IIoT em cenários brownfield de forma modular (por camadas CPS) e incremental (pequenos projetos).

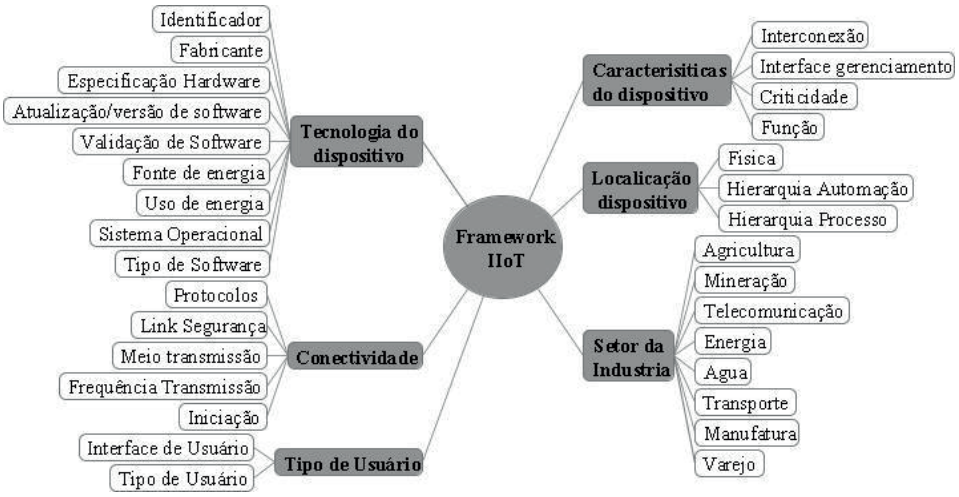

Fig. 6. Detalhamento framework IIoT Figura 5 (Fonte: Adaptado [1])

Conforme a Figura 5, inicia-se com a etapa de pré-implementação ou preparação, destacando-se como um passo essencial para efetiva implementação de projetos IIoT. O foco é preparar a organização em termos de entendimento da situação atual, oportunidades, recursos necessários, mudança cultural e demandas de reestruturação interna, além do desenvolvimento de parcerias.

Na fase de implementação, sugere-se o uso da junção das camadas 5C do sistema CPS e o framework de IIoT como referências para orientar projetos. De acordo com a abrangência do projeto é possível implementar a infraestrutura de IIoT em uma ou mais camadas da arquitetura 5C de CPS. Na arquitetura 5C, na 1ª camada (conexão), o foco é aquisição de dados, do processo, da produção e máquina monitorando, por exemplo, a condição. Na 2ª camada (conversão) o objetivo é aplicar recursos de análise de dados coletados na camada anterior, para identificar padrões, correlações e predição de vida útil remanescente [9].

A 3ª camada (ciber-física) atua como concentrador de todas as informações da rede de máquinas conectadas. A grande massa de dados coletados é processada para extrair informações de valor. Nesta camada, os dados entre máquinas são comparados através de ferramentas de análise e similaridades entre dados em tempo real são processados conduzindo a ações como previsão de comportamento futuro das máquinas [9]. A

correta implementação até a 3ª camada (ciber-física) é de extrema importância para se alcançar resultados efetivos nas 4ª e 5ª camadas.

A 4ª camada (cognição) é onde se aplicam sistemas de suporte a decisão. A partir desta camada a informação é transformada em conhecimento e é apresentado através de infográficos aos especialistas para tomadas de decisão e priorização por exemplo. Na 5ª e última camada (configuração), com base nas decisões da camada anterior, é estabelecido o feedback de ações corretivas e preventivas do mundo virtual para o físico, sendo que tais ações têm foco em autoconfiguração e auto adaptação das máquinas monitoradas [9].

Na Figura 7 apresenta-se uma correlação entre princípios e índice de maturidade da I4.0 e a arquitetura 5C de CPS [13]. Através da figura tem-se uma visão dos princípios para a manufatura atingir o nível de I4.0 (interconexão, transparência, decisão descentralizada e assistência). Atingindo tais princípios alcança-se as capacidades conforme índice de maturidade (computação, conectividade, visibilidade, transparência, predição e adaptação). Com a arquitetura 5C apresenta-se em termos macro os cinco níveis a serem implementados para atender os princípios I4.0 e alcançar as referidas capacidades (Índice de Maturidade 4.0).

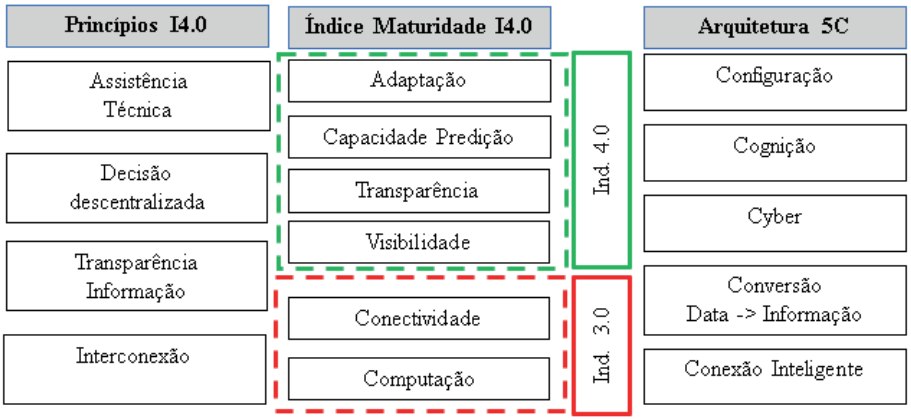

Fig. 7. Comparativo dos Princípios e Índice Maturidade I4.0 e Arquitetura 5C (Fonte: Adaptado [13])

Um fato relevante, conforme observa-se na Figura 7 é que no atual cenário (Industria 3.0) muitas indústrias já possuem parte da jornada iniciada. Outro ponto é que mesmo que não houvesse as necessárias adequações demandadas pela I4.0, ainda assim existiriam projetos relacionados a TA e TI devido a outros fatores, como exemplo, mudança de produto, melhorias para aumento produtividade, segurança e confiabilidade. Somando-se a estes fatos, a possibilidade de parcerias entre academia e profissionais com foco em melhoria e/ou validação de conceitos, frameworks e arquiteturas, caracteriza-se um excelente meio para desenvolver boas práticas na condução de projetos de IIoT e outros relacionados à I4.0 para vantagem competitiva na manufatura.

Concluindo a análise do mapa orientativo (Figuras 5 e 6), a etapa de pós implementação tem o papel de validar, acompanhar resultados e consolidar os conhecimentos

adquiridos através dos projetos pilotos. As informações levantadas atuam como base para definição de requisitos para elaboração de um *roadmap* para projetos de maior escala ou até mesmo de digitalização de toda planta, além de contribuir para aumento de maturidade e mudança cultural dentro das organizações.

5 Considerações Finais

Diante do questionamento em como as organizações poderiam se preparar para implementação de projetos pilotos de IIoT, conclui-se que seria possível alavancar bons desenvolvimentos nos aspectos técnicos, metodológicos e culturais relativos a IIoT. Para tal, sugere-se como base o mapa orientativo proposto nas demandas atuais de projetos dentro da manufatura. Quanto as hipóteses referentes às dificuldades de implementação de IIoT, conclui-se que as três são verdadeiras ao contexto avaliado.

A falta de conhecimento estruturado relativo ao nível de implementação de IIoT dentro das empresas (H1), se confirma devido o atual estágio de amadurecimento no campo de pesquisa e aplicação. No tocante a falta de priorização de projetos de IIoT, devido à dificuldade da avaliação da relação custo e benefício (H2), esta questão se correlaciona a anterior - a falta de entendimento dificulta descrever elementos que justifiquem o retorno sobre investimento e consequentemente uma tomada de decisão gerencial.

Já a falta de sinergia entre indústria e academia para pesquisa, desenvolvimento e aplicações de IIoT (H3), representa uma oportunidade de solução para as duas anteriores, porém envolvem ações nas esferas política, econômica e estratégica tanto do setor público como privado. Ressalta-se que já existem iniciativas em relação a parceiras entre instituições públicas e privadas, mas pode-se acelerar este processo de amadurecimento rumo a transformação digital através de ações mais abrangentes em termos de números participantes, estudos e iniciativas de aplicação.

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Review: Cadenas de Suministro, desde la Colaboración de Eslabones a la Gestión de Cadenas Sustentables

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Abstract. The purpose of this paper is to present a review, along the time, of the concept of supply chain and some elements specifically related to agrifood supply chain, collaboration along them, and how their different configurations can or not, affect the environment. The methodology used was article searching through key words in online journals' databases. Based on the review of 65 articles, a taxonomy is proposed that allows to identify 41 concepts; articles dated between 1985 and 2020. For each decade is possible to identify what are the main themes of discussion. Thus, it is shown that in the beginning of the analysis, supply chain was centered on logistic aspects and movement of materials from a supplier to final customers. In contrast, in the last period analyzed, the concerns are related to collaboration, environment protection and new emerging chains.

Keywords: Cadenas de suministro, Cadenas agroalimentarias, Revisión de literatura.

1 Introducción

El presente artículo muestra la evolución del concepto de cadena de suministro [CdS] y algunas de sus particularidades, como lo son las cadenas de suministro agroalimentarias [CdSA], las redes de cadenas de suministro [RCdS] y la colaboración para finalizar con una revisión de las nuevas tendencias incorporando elementos de sostenibilidad, capacidades dinámicas, CdS emergentes y CdS verdes. Al hablar de CdS, en la literatura es posible encontrar variadas definiciones de CdS, desde aquellas que se refieren a un proceso de carácter funcional a las que se enmarcan en una perspectiva de filosofía empresarial. Algunos autores la vinculan a los procesos que involucran a los proveedores y sus clientes y conectan empresas desde la fuente inicial de materia prima hasta el punto de consumo del producto acabado, así como con las funciones dentro y fuera de una empresa que garantizan el proveer de productos y servicios a sus clientes.

Esta revisión contempla 65 artículos desde el año 1985 al 2020, seleccionados a través de criterios de búsqueda específicos en bases de datos de revistas electrónicas y en buscadores de revistas especializadas. Respecto a los criterios de búsqueda se utilizaron aquellos relacionados a cadena de suministro, cadena de suministro agrícola o agroalimentaria, colaboración en la cadena de suministro, redes de cadenas de suministro, cadenas de suministro y sustentabilidad. El artículo se organiza en cinco apartados, este primer apartado introductorio que entrega la idea de lo que trata el artículo y cómo este se organiza. El segundo apartado entrega el enfoque metodológico bajo el cual se desarrolló el artículo. El apartado tres, desarrolla en extenso la revisión conceptual realizada y es el insumo principal para presentar la taxonomía en el apartado cuatro. Finalmente, el quinto apartado presenta las conclusiones.

2 Metodología

La búsqueda se realizó durante el periodo comprendido entre 2015 y 2020, en bases de datos de revistas electrónicas y en buscadores de revistas especializadas, lo que incluye publicaciones en portales como: Elsevier [www.sciencedirect.com], Emerald [www.emeraldinsight.com], Springer [www.springerlink.com], Academic Journals [http://www.academicjournals.org] , Ebsco [http://www.ebscohost.com], AgEcon [http://ageconsearch.umn.edu], Scielo Brasil [http://www.scielo.br]. Respecto a los criterios de búsqueda se utilizaron aquellos relacionados a industria agroalimentaria, cadena de suministro agrícola, gestión de la cadena de suministro, redes de suministro, colaboración en la CdS y sustentabilidad a lo largo de la misma. Como resultado de la búsqueda, finalmente, se seleccionaron aquellos que cumplen con el requisito de describir comportamiento y configuraciones de CdS, haber sido publicados desde el 1985 en adelante y hasta 2020, generando una base de análisis de 65 artículos. En tanto el alcance y perspectiva de la revisión es de 65 artículos que se distribuyen en un periodo de 35 años y fueron obtenidas en su mayoría de revistas científicas, libros, informes y documentos de trabajo.

3 Revisión de la Literatura

3.1 Cadena de Suministro – CdS

Tal como señala Valenzo, Martínez, y Pedraza [1] el concepto de cadena de suministro se origina en la literatura de la logística [2, 3], donde inicialmente, el énfasis estaba en la facilitación del movimiento del producto y la coordinación de la oferta y la demanda entre un proveedor y un comprador. Al revisar la literatura existente, es posible encontrar variadas definiciones de CdS, desde aquellas que se refieren a un proceso de carácter funcional, aquellas que podrían enmarcarse en la perspectiva de la filosofía empresarial y las últimas tendencias que hablan de cadenas de suministro sustentables o cadenas verdes. En primer lugar, la Asociación para la Gestión de Operaciones (APICS) define en su diccionario el término CdS como: El conjunto de todos los procesos que involucran a los proveedores y sus clientes y conectan empresas desde la fuente inicial

de materia prima hasta el punto de consumo del producto acabado y las funciones dentro y fuera de una empresa que garantizan que la cadena de valor pueda elaborar y proveer de productos y servicios a sus clientes [4].

Lee y Billington [5] señalan que una CdS se comporta como una red de trabajo para las funciones de búsqueda de material, Lummus [6] asume la CdS como una red de entidades por donde el material fluye, teniendo en cuenta que estas entidades pueden ser proveedores, transportistas, fábricas, centros de distribución, comerciantes y clientes finales. Algo parecido es lo que Christopher [7] define como una red de organizaciones relacionadas a través de conexiones en dirección a los proveedores o en dirección contraria hacia la creación de un producto o servicio y lo denomina upstream/aguas arriba y downstream/aguas abajo respectivamente.

Carter, Rogers y Choi [8] desarrollan una teoría sobre la cadena de suministro, aportando con una conceptualización inicial, base para próximos estudios. Ellos plantean que los investigadores de la cadena de suministro han comenzado a moverse más allá del día a día comprador-proveedor y comienzan a observar la red de suministro más que los pequeños nodos de la Red [9, 10]. Por otro lado Janvier-James [11] plantea que existen dos grupos de definiciones: El primero de ellos centrado en conseguir una cadena de suministro eficaz, resaltando la necesidad de tener claridad sobre la procedencia y destino de las mercancías que transitan a lo largo de la cadena de suministro, comenzando desde las materias primas, combinando una serie de actividades de valor añadido y terminando con la transferencia de un bien acabado a los consumidores [12, 13, 14]. El segundo grupo son consideradas por Mentzer et al. [17] como definiciones más complicadas ya que entregan una vista amplia de la CdS y esperan integrar a ella actividades adicionales a la función natural de una CdS [15, 16, 17].

Hace unos años y como resultado de las cadenas de suministro extendidas modernas, ha surgido un nuevo concepto: cadenas de suministro sostenibles o SSCM [del inglés sustainable supply chain management], obligando a cambiar el enfoque de la sostenibilidad corporativa a un enfoque integrado en todas las dimensiones de la cadena de suministro [18] teniendo en cuenta las dimensiones de empresa, medio ambiente y sociedad [19].

El concepto de SSCM se puede definir como la gestión de material, información y los flujos de capital, así como la cooperación entre empresas a lo largo de la cadena de suministro, teniendo como objetivo las tres dimensiones del desarrollo sostenible, que se derivan de los requisitos de los clientes y las partes interesadas [20]. Ahi y Searcy [21] plantean que la sostenibilidad se define comúnmente como la utilización de recursos para satisfacer las necesidades del presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades. Según [22] las primeras iniciativas de sostenibilidad tendieron a centrarse en cuestiones ambientales, pero, con el paso del tiempo, adoptan cada vez más un triple enfoque de fondo: medioambiental, económico y social. Como este enfoque implica un mayor número de factores que interactúan, se puede esperar un mayor grado de complejidad.

3.2 Cadena de Suministro Agroalimentaria - CdSA

Tal como señala Chen [23] en [24] en los últimos años la industria agroalimentaria ha reconocido y abrazado la gestión de la cadena de suministro como concepto clave para su competitividad. La rápida industrialización de la producción agrícola, el oligopolio en el sector de distribución de alimentos, el rápido avance de la tecnología y las comunicaciones aplicadas a la logística, las preocupaciones de los clientes, las normas de seguridad alimentaria del gobierno, las exigencias de calidad, la aparición de alimentos modernos, la creciente importancia de la integración vertical y alianzas horizontales, así como la aparición de una gran cantidad de empresas multinacionales son sólo algunos de los desafíos del mundo real que han llevado a la adopción de la gestión de la cadena de suministro en el sector agroalimentario.

En general, una CdS agroalimentaria se compone de un conjunto de actividades en secuencia, desde "la granja al tenedor", incluyendo la agricultura [es decir, el cultivo de la tierra y la producción de cultivos], procesamiento / producción, los ensayos, envasado, almacenamiento, transporte, distribución y comercialización [25]. Estos escalones operativos son apoyados por actividades logísticas, servicios financieros y técnicos, mientras que sobre ellos mismos circulan cinco tipos de flujo: el material físico y los flujos de productos; los flujos financieros; los flujos de información; flujos de proceso y la energía y los flujos de recursos naturales.

Al revisar la literatura, algunas definiciones presentan la cadena agroalimentaria como aquella referida a toda cadena vertical de actividades, desde la producción en el establecimiento agropecuario, pasando por la etapa de procesamiento y por la distribución mayorista y minorista en otras palabras el espectro completo del cultivo a la mesa, sin importar cómo se organiza o cómo funciona la cadena [26]. En otros casos se utiliza para abarcar el continuum de procesos económicos vinculados a los alimentos, que se inician en la explotación agropecuaria y culminan en el consumo [27]. Para Fischer et al. [28] los consumidores cada día son más exigentes y esperan que la comida sea de alta calidad en términos de atributos físicos, las características del proceso de elaboración y aspectos sociales como el bienestar de los animales, el comercio justo y la gestión ambiental. Por tanto abordar estas necesidades de los consumidores exige una mayor coordinación de acciones de las empresas de toda la cadena [29, 30].

Las CdS agroalimentarias están evolucionando rápidamente en el tiempo con el fin de seguir los cambios agroalimentarios, siendo los mayores desafíos: la rápida urbanización, el crecimiento de los mercados, la financiación del sector, las preocupaciones por obtener alimentos de alta calidad y seguridad alimentaria, las poblaciones rurales regionales que no cumplen con los requisitos planteados por las empresas dominantes del sector, los efectos del cambio climático en la agricultura y el establecimiento de responsabilidad social empresarial (RSE). Por lo tanto, el reconocimiento de los problemas críticos que deben ser abordados por los interesados en las CdS Agroalimentaria surge como un requisito previo para la gestión de tales cadenas, a todo nivel, y así garantizar su eficiencia y sostenibilidad en general [24].

Handayati, Simatupang y Perdana [31], señalan que los productos agrícolas tienen un papel importante en la economía mundial, además la cadena de suministro de productos agrícolas se ha convertido en un tema candente porque los consumidores cada vez son más conscientes y preocupados por la disponibilidad y la inocuidad de los alimentos que se consumen [32]. Ellos exigen disponer de más información no sólo sobre la disponibilidad de un producto en los supermercados, sino también sobre sus actividades de producción, comercialización, distribución, transporte y transformación [33] y desarrollan un comportamiento cambiante porque ya saben lo que necesitan y qué valor esperan del producto que compran, por lo tanto es importante para una empresa facilitar este tipo de creación de valor.

3.3 Red Cadena de Suministro – RCdS

Es posible observar que la evolución del concepto de CdS ha sido tal que es posible hablar de Red/CdS, haciendo la siguiente distinción: se considera como CdS aquélla que sea lineal y unidireccional, sin embargo una red de suministro no es más que una CdS con bucles, relaciones laterales, intercambios, de material e información, en ambos sentidos, teniendo a la empresa focal como punto de referencia [34]. Algunos autores postulan, que es posible denominar como red de suministro a la gigantesca cantidad de interconexiones que se desarrollan como resultado de las interacciones entre los nodos de la CdS, tal como lo presentó García [35] o lo que se le denomina red de suministro en el enfoque de sistemas de medición del rendimiento que se presentó Alfaro, Ortíz y Rodríguez [36].

Sin embargo son Lamming et al. [34] quienes platean una primera clasificación de las redes de suministro y para ello establecieron que una Red de Suministro [RdS] es una extensión de las CdS, que buscan proporcionar y explicar la complejidad comercial asociada con la creación y despacho de productos y servicios de la fuente de materiales hasta el destino final o mercado cliente, alrededor de las actividades aguas arriba y aguas debajo de una empresa focal como punto de referencia [37]. Por tanto, al considerar según la definición de [34] la RdS como una extensión de la CdS surge un nuevo concepto a revisar, el enfoque de colaboración. En definitiva, se requiere un alto nivel de integración en la cadena de suministro; sin embargo no es suficiente para alcanzar el máximo nivel de competitividad y crecimiento de la industria: se necesitan nuevos modelos inter-empresariales que hagan a las empresas todavía más competitivas, ágiles y eficientes [38]. Barratt [39] plantea que para comprender el significado de la colaboración a lo largo de la CdS es necesario responder tres preguntas: ¿Por qué necesitamos colaborar?; ¿Dónde podemos colaborar?; ¿Con quién debemos colaborar? y a la vez ser capaces de reconocer los elementos presentes en la colaboración.

Actualmente, no se pone en duda que la CdS es clave y vital para el éxito de las empresas. En muchos casos, su capacidad de competir se ha vinculado directamente con su capacidad de colaborar con otras empresas. Muchos escritores [40, 41, 42, 43, 44, 45] han reconocido un aumento en la necesidad de colaboración, haciendo hincapié

en el establecimiento de relaciones de trabajo más estrechas y a largo plazo, incluso en varios niveles de la cadena como una forma de construir cadenas cada vez más eficientes para ofrecer un valor excepcional a los clientes [46] convirtiéndose para muchas empresas en una necesidad, más que una opción.

Sin embargo, la colaboración en la cadena de suministro no siempre es fácil de lograr, incluso cuando las restricciones de comunicación del pasado, con respecto al intercambios de datos y de información eficiente entre los miembros de la cadena, han sido superados con el uso de tecnología y el desarrollo de aplicaciones e-business [46]. Es claro que existe una gran cantidad de beneficios asociados a la colaboración en la CdS. Una primera aproximación, para visualizar estos beneficios, es a nivel macro pensando en la reducción de costos totales o el aumento de los ingresos [47], pero de igual forma existen riesgos, tal como lo señalan Dwyer, Schurr, y Oh [48], el más obvio es el fracaso en el intento de colaboración, lo que lleva consigo la pérdida de importantes inversiones en dinero, tiempo y retraso o abandono de los planes de negocio, además un riesgo inherente al fracaso es la exposición a la competencia.

Para Saleh y Roslin [49] la aparición de esta competencia ha aumentado la necesidad de que las empresas a lo largo de toda la cadena de suministro cooperen, coordinen, colaboren e integren esfuerzos, para generar un alto valor de retorno a todos los participantes de la cadena de suministro. Aun cuando lo anterior es un escenario ideal, la realidad muestra que los resultados de la integración de la CdS [SCI] no han sido exitosos en la mayoría de los casos, debido a la incapacidad de las empresas de colaborar con los socios de la cadena de suministro de manera eficaz y eficiente.

3.4 Nuevas Tendencias en la CdS

Pérdidas y desperdicios. Las pérdidas o desperdicios de alimentos son las cantidades de material comestible que se pierden a lo largo de la CdS de alimentos en diversas etapas, incluida la recolección, el almacenamiento postcosecha y la manipulación, procesamiento, distribución y consumo [50]. Teniendo en cuenta lo anterior, Balaji y Arshinder [51] señalan que el desperdicio a lo largo de las cadenas de frutas y hortalizas es muy alto en mercados emergentes, por tanto identifican 16 grandes causas de este desperdicio lo que permite a los diseñadores de CdS, gerentes y diseñadores de política pública tener mayores implicaciones en la seguridad alimentaria y la conservación de los recursos ambientales. Algunas de estas causas son: Falta de instalaciones frigoríficas, falta de métodos científicos de aprovechamiento, infraestructura logística deficiente, diseño pobre de la red logística, falta de métodos modernos de procesamiento y falta de diseño y métodos modernos de embalaje.

Cadenas de Suministro Emergentes. Anastasiadis y Poole [52] plantean que en gran medida, el concepto de desarrollo de North [53] coincide con la mejora creciente en la estructura y el comportamiento del mercado, produciendo nuevos cambios. Estos cambios, como lo que plantean Lorentz, Kittipanya-ngam y Srai [54] señalan el caso de

empresas en "mercados avanzados" que expandían sus operaciones hacia "mercados emergentes" para entender cómo las características de los mercados emergentes afectan las redes de suministro de cadenas de alimentos de empresas internacionales. Entre los hallazgos de [54] destacan la importancia, en primer lugar, de las instituciones y estructuras y, en segundo lugar, de las estrategias de los actores del mercado primario y secundario, para posibilitar la formación de nuevas CdS y redes de suministro. Detectando cuatro factores que afectan la aparición de CdS: La estructura propia de las cadenas y la capacidad de sus actores; Control de la calidad de los bienes y servicios; Infraestructura y procesos para administrar nuevos productos; Y la importancia de la configuración geográfica de las redes de suministro, pensando en la internacionalización de estas cadenas.

Por lo general, la estrategia de una empresa se formula a nivel de la alta dirección y luego se aplica en toda la organización. Sin embargo, las pequeñas y medianas empresas o empresas familiares, como el caso de la industria alimentaria en las economías emergentes, dependen en gran medida de un único decisor [55]. Incluso en el sector agrícola donde están surgiendo nuevas estrategias empresariales colectivas, la naturaleza de estas organizaciones genera problemas de toma de decisiones debido a las diversas preocupaciones de su base social [56]. Aspectos como la confianza del propietario con respecto a los miembros de la red de suministro [57] y la calidad de las relaciones entre los participantes de la CdS [58] son de vital importancia.

Cadenas de Suministro y Capacidades Dinámicas. Junto al estudio de la SSCM, Beske, Land y Seuring [59] ponen atención a un nuevo concepto denominado capacidades dinámicas [DC] examinando ambientes e industrias dinámicamente muy cambiantes como el caso de la industria alimentaria, en la cual los clientes tienen altas expectativas de seguridad alimentaria y una creciente demanda de alimentos producidos de manera sostenible. Las capacidades dinámicas fueron estudiadas primero por Teece, Pisano y Shuen [60] para explicar la ventaja competitiva y el rendimiento a alta velocidad frente al cambio dinámico de los mercados. Helfat et al. [61] definen las capacidades dinámicas como la capacidad de una organización para crear, extender o modificar deliberadamente su base de recursos y como tal mejorar la evaluación económica otorgada por sus competidores. Siguiendo las definiciones de [61], Beske et al. [59] plantean que las prácticas propuestas en la SSCM forman la base para desarrollar capacidades dinámicas, debido los distintos cambios que enfrentan las CdS [por ejemplo: manejo de los proveedores cuando cambian las condiciones en el entorno, incorporar todos los objetivos corporativos de responsabilidad social].

Mejora del Medio Ambiente a Través de la Colaboración de la Cadena de Suministro. La selección de proveedores adecuados de acuerdo con los criterios para la gestión de cadenas de suministro verdes, es crucial para las empresas en la lucha contra la contaminación y el cuidado del medioambiente [62]. Esta idea es validada, años más tarde, por Chavez et al. [63] quienes hacen hincapié en la necesidad de cooperar y colaborar a lo largo de toda la cadena, buscando la mejora del impacto sobre el

medioambiente y junto con ello un mejor desempeño económico. Por otro lado, en el 2010 Bai y Sarkis [64], sostenían que la selección de proveedores adecuados juega un papel crucial en GSCM ya que se transforma en una herramienta de apoyo al momento de seleccionar los mejores proveedores de acuerdo con criterios ambientales. Por lo tanto, se puede decir que, según muchos investigadores, la colaboración con los proveedores juega un papel crucial en la implementación exitosa de GSCM. Finalmente, los proveedores desempeñan un papel fundamental, en la gestión de la CdS verde, ya sea en las fases iniciales como en las finales, logrando a través de la logística crear el vínculo entre proveedores, clientes y empresas focales, quienes bajo un mismo enfoque de gestión de cadenas de suministro verdes, aportan a la mejora del medioambiente [65].

4 Taxonomía

La siguiente taxonomía muestra cómo a lo largo del tiempo el concepto de cadena de suministro ha ido cambiando y se le han ido integrando elementos propios de un mundo globalizado. En este caso en particular se hace una exploración a las cadenas de suministro agroalimentarias, como un tipo particular de cadenas de suministro que cumplen con abastecer a todo el mundo de alimentos frescos desde la granja a la mesa.

El análisis realizado, permite observar en la última mitad de los 80's, conceptos que hacen referencia a vincular la CdS a la logística y el movimiento de productos, apareciendo incipientemente los conceptos de sustentabilidad, medio ambiente y la colaboración a lo largo de la cadena. Conceptos como la necesidad de colaborar, establecer relaciones a largo plazo y estables entre las entidades presentes se observan en los 90´s, al mismo tiempo se reconoce que colaborar también tiene dificultades, incipientemente aparecen los conceptos de capacidades dinámicas de adaptación. En los 00's se refuerza lo que venía ocurriendo en los 90´s respecto a la colaboración, pero se comienza a visualizar la CdS como una red de cadenas, que son capaces de competir de forma conjunta, colaborando y gestionando de forma sostenible. Finalmente en la década del 2010, se incorporan los conceptos de cuidar la pérdida de productos, los mercados emergentes y quién toma las decisiones a lo largo de la CdS.

Id	Año	Autor	Logística	Movimiento de productos	Procesos que conectan productos y clientes	Red de trabajo	Red de entidades	Red de organizaciones	Conexión con proveedores	Cadena como una Red	CdS eficaz	CdS realiza otras actividades	CdS Sostenible	Gestión de material información Y los flujos de capital	Cooperación entre empresas	Satisfacer necesidades presentes sin comprometer el futuro	Medioambiental económico y social	Gestión de la CdS para la competitividad	Reconocer problemas típicos en la CdS	Actividades en secuencia	Producción hasta el consumo	Necesidad de coordinación	Consumidores exigentes	Red de suministro	Complejidad comercial a lo largo de la CdS	Necesidad de colaboración	Relaciones de trabajo más estrechas	Relaciones de largo plazo	Dificultades de la colaboración	Reducción de costos	Aumento de ingresos	Riesgos de la colaboración	Fracaso en el intento de colaborar	La competitividad requiere cooperar, coordinar y colaborar	Cuidar las pérdidas de alimentos en las CdSA	Nuevos mercados afectan las redes de suministro	Dificultad por un único decidor	Se requiere confianza del decidor hacia la CdS	Calidad de las relaciones entre los participantes de la CdS	Capacidades dinámicas de la CdS	Ventaja competitiva y rendimiento	Capacidad para crear, extender o modificar sus recursos	Proveedores responsables con el medio ambiente	Crear el vínculo entre proveedores, clientes y empresas locales
1	2010	Valenzo et al	X	X																																					
2	1985	Bowersox et al	X	X																																					
3	1985	Jones y Riley	X	X																																					
4	2013	Blackstone			X																																			
5	1993	Lee y Billington				X																																		
6	1997	Lummus					X																																	
7	1999	Christopher						X	X																															
8	2015	Carter, Rogers y Choi								X																														
9	2013	Mena, Humphries y Choi									X																													
10	2009	Choi y Dooley								X																														
11	2012	Jaimez-James										X																												
12	1998	Beamon										X																												
13	2020	Bridgfield group										X																												
14	2009	Pienaar										X																												
15	1999	Chow											X																											
16	2002	Ayers											X																											
17	2001	Mentzer et al											X																												
18	2014	Trifter												X																										
19	2005	Klinkerfie, Singhal y Van Wassenhove												X																										
20	2008	Scarmy y Miller												X	X																									
21	2013	Aby y Searcy												X		X																								
22	1987	WCED												X			X																							
23	2006	Chen																X																					
24	2013	Tsolakis et al																X	X																				
25	2012	Iakovou, Vlachos y Achillas																		X																				
26	2000	Hobbs, Cooney y Fulton																		X																				
27	1997	Obschakko																			X																			
28	2010	Fischer et al																				X																		
29	2001	Boger																				X																		
30	2005	Méndez y Valcarcel																				X																		
31	2015	Handayati , Simatupang y Perdana																					X																	
32	2007	Hasuti																					X																	
33	2009	Ahumada y Villalobos																					X																	
34	2000	Lamming et al																						X	X															
35	2006	García																						X	X															
36	2007	Alfaro, Ortiz y Rodríguez																						X	X															
37	2009	López																							X															
38	2003	Aarseth et al																								X	X													
39	2004	Beamon																								X	X													
40	1998	Christopher																								X	X													
41	1996	Gattorna et al																								X														
42	2001	Gunasekaran, Patel y Tirtoglu																								X	X													
43	1994	Hines																								X														
44	1993	Lamming																								X	X													
45	1990	Lewis																								X	X													
46	2007	Manopoulos et al																								X		X												
47	2003	Sahay																									X	X												
48	1987	Dwyer y Schurr																										X												
49	2015	Saleh y Reslin																											X											
50	2011	Gustavsson et al																											X											
51	2016	Baltij y Aslander																												X										
52	2015	Anastasiadis y Poole																												X										
53	1990	North																													X									
54	2013	Lorentz, Kittpanya y Snai																													X									
55	2005	Feltham, Feltham y Barnett																														X								
56	2010	Ortiz, Moreno y Mongues																															X							
57	2007	Brunelo y Farr-Wharton																																X						
58	2006	Vasiliadou y Morris																																	X	X				
59	2014	Beske, Land y Seuring																																	X	X				
60	1997	Tessa, Plumo y Shien																																	X					
61	2007	Hellfi et al																																		X				
62	2011	Tseng																																			X			
63	2016	Chavez et al																																			X			
64	2010	Bai y Sarkis																																				X		
65	2019	Tseng et al																																						X

Fig. 1. Taxonomía de conceptos cadena de suministro a lo largo del tiempo, elaboración propia.

5 Conclusiones

El estudio de las cadenas de suministro, a lo largo del tiempo, ha ido tomando fuerza porque permite describir la forma en que todos los productos o servicios llegan a los consumidores. Inicialmente se vinculaba mucho con la logística y el flujo de materiales desde un proveedor al consumidor, pasando por el distribuidor, actualmente esa visión ha cambiado y el estudio de CdS se amplía a estudiar cómo estas cadenas se configuran, quiénes forman parte de ella y que entidades la componen, cómo se relacionan y quién toma las decisiones. El estudio de cadenas perecederas y en especial las agroalimentarias, en los últimos años sitúa al consumidor como actor principal, muy informado y exigente, preocupado de la pérdida de alimentos y la producción sustentable sin dañar el medio ambiente.

El presente review, permite conocer cómo este concepto ha ido cambiando en el tiempo y se le han ido incorporando distintas variables que hacen más complejo su estudio. En primer lugar, entender que las CdS no son empresas individuales, sino una red de colaboración que en conjunto debe competir contra otra red de suministro y para ganar esa competencia y lograr situarse como líder del mercado es importante configurar una cadena flexible, eficaz y moderna, que esté atenta a los cambios del entorno, a la incorporación de tecnología y a la constante mejora de sus procesos que fluyen a lo largo de ella.

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Applying a Decision Model to Evaluate the Influence of Digital Transformation Technologies on TOGAF Architecture Principles

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Abstract. Organizations all over the world are going through the process of digital transformation. Enterprise Architecture (EA) is a method and an organizing principle that aligns functional business objectives and strategies with an IT strategy and execution plan. The Enterprise Architecture provides a guide to direct the evolution and transformation of enterprises with technology. Principles are a key concept in the definition of EA, they assist in recognizing the organization vision and validating the outcomes. The aim of this paper is to develop a decision model to evaluate the influence Digital Transformation (DT) technologies have on the architecture principles proposed by TOGAF. A literature review was conducted, and five main DT Technologies applied in the EA scope were identified. With that, a decisional model was created based on a decision-making method called PROMETHEE. The twenty-one architecture principles proposed by TOGAF were evaluated and the influence the technologies exercised on the principles were identified. As a result, Big Data and Cloud Computing technologies were indicated as having the greatest effect over the analyzed principles.

Keywords: Enterprise Architecture; Architecture Principles; TOGAF; Digital Transformation; Technologies.

1 Introdução

As organizações no mundo todo estão passando pelo processo de transformação digital. De acordo com Nightingale e Rhodes [22], empresas são sistemas complexos e altamente integrados, compostos por processos, organizações, informações e tecnologias de suporte, com interdependências multifacetadas e inter-relações além de suas fronteiras. A compreensão, a engenharia e a gestão dessas complexas dimensões sociais, técnicas e de infraestrutura são fundamentais para alcançar e sustentar o desempenho das empresas [22]. A fim de fornecer esse suporte e atacar o problema de alinhamento de negócios/TI, a Arquitetura Empresarial (AE) surgiu. Adotando uma abordagem holística, a AE foca não apenas nos aspectos técnicos, mas também nos

vários aspectos da empresa sobre os quais os sistemas de tecnologia da informação (TI) operam [3].

A arquitetura empresarial (AE) é um método e um princípio organizador que alinha objetivos e estratégias funcionais de negócios a uma estratégia de TI e plano de execução. A arquitetura corporativa fornece um guia para direcionar a evolução e transformação das empresas com tecnologia. Isso, por sua vez, torna a TI um ativo mais estratégico para implementar com sucesso uma estratégia de negócios moderna [13].

De acordo com Proença e Borbinha [24], a literatura atual da AE mostra foco no refinamento dos métodos existentes. Um ponto fraco é a atenção para os desafios decorrentes da aplicação de conceitos de AE em ambientes organizacionais específicos. Ainda não existem instrumentos adequados para avaliar o estado atual e identificar oportunidades de melhoria. Com isso, organizações tem enfrentado dificuldades em iniciar melhorias nos procedimentos de gestão da AE.

Kempegowda e Chaczko [15] afirmam que os princípios de arquitetura ajudam na obtenção da visão da organização e na validação dos resultados. Dá à equipe a capacidade de decidir durante a execução da estrutura do AE. Ele também fornece Governança para verificar e auditar a implementação do AE. Os princípios são um conceito-chave na definição de AE [11] e auxiliam na realização da visão da organização e na validação dos resultados. Eles dão a equipe a capacidade de decisão durante a execução da estrutura da AE. Além disso, fornece governança para verificar e auditar a implementação da AE. É fundamental que as empresas definam princípios que serão utilizados pelos Arquitetos para a tomada de decisões diárias [15].

O objetivo deste artigo é apresentar um modelo de decisão para avaliar os impactos das tecnologias de transformação digital sob os princípios de arquitetura propostos pelo TOGAF. A primeira seção contempla a introdução e os objetivos de pesquisa. Na segunda seção os conceitos teóricos que fundamentam o desenvolvimento deste trabalho são apresentados. A terceira seção contempla a estratégia de pesquisa abordada e em seguida, na quarta seção os resultados obtidos são apresentados. Por fim, a quinta seção traz as conclusões e discussões dos resultados obtidos.

2 Revisão de Literatura

2.1 Arquitetura Empresarial (AE)

A arquitetura empresarial (AE) representa a estrutura de uma empresa e consiste nos principais componentes de uma organização, tais como seus objetivos, estruturas organizacionais, infraestrutura de informações e processos de negócio. Essa arquitetura ajuda a organização ao determinar como a mesma pode atingir, de maneira efetiva, seus objetivos atuais e futuros. A performance de uma empresa, como as inovações geradas dentro da companhia, a reengenharia dos processos de negócio, e a qualidade e prontidão do fluxo de informações, podem ser melhoradas se o sistema de AE representar fielmente as características e natureza da organização [36]. De acordo com Korhonen e Halén [16], AE vem sendo sugerida como uma disciplina para assegurar uma estrutura coerente, tornar visível o sistema organizacional subjacente e para facilitar possíveis mudanças.

Atualmente, existem vários frameworks de arquitetura empresarial que podem ser usadas por organizações ou empresas de acordo com suas necessidades. Dentre os padrões existentes, quatro deles se destacam: Zachman Framework, Gartner Framework, Federal Enterprise Architecture Framework (FEAF) e The Open Group Architecture Framework (TOGAF) [26].

TOGAF é um padrão de arquitetura empresarial aberto e abrangente que contém diversos componentes, dentre os quais, o Architecture Development Method (ADM) se destaca, sendo o núcleo do TOGAF. O ADM descreve um processo iterativo para o desenvolvimento da AE, com a ajuda de diversas fases (Fase Preliminar, Visão de Arquitetura, Negócios, Sistemas de Informação, Tecnologia, Oportunidades e Soluções, Planejamento de Migração, Governança de Implementação, Gerenciamento de Mudanças na Arquitetura, Gerenciamento de Requisitos).

Quatro domínios de arquitetura são cobertos pelo TOGAF: a) Arquitetura de Negócios, b) Arquitetura de Dados, c) Arquitetura de Aplicativos e d) Arquitetura de Tecnologia. Estes domínios são frequentemente aceitos como subconjuntos do todo da arquitetura empresarial [31]. O framework TOGAF, um padrão do The Open Group, é uma metodologia e estrutura comercialmente consolidada de arquitetura empresarial usada pelas principais organizações mundiais visando o aumento da eficácia dos negócios [30].

O Zachman framework para Arquitetura Empresarial publicado por John Zachman em 1987 e é considerado um dos pioneiros nesse domínio [12]. O Framework é baseado nos princípios da arquitetura clássica que estabelecem um vocabulário comum e um conjunto de perspectivas para descrever sistemas empresariais complexos [32]. O Zachman Framework possui seis perspectivas: Planejador, Proprietário, Designer, Construtor, Subcontratado e Usuário. A segunda dimensão do framework lida com as seis perguntas básicas: o que, como, onde, quem, quando e por que. A estrutura não fornece orientação sobre sequência, processo ou implementação, mas se concentra em garantir que todas as visualizações sejam bem estabelecidas, garantindo um sistema completo, independentemente da ordem em que foram estabelecidas [37].

O Gartner define a AE como um processo contínuo que envolve avaliar o estado atual da arquitetura, definir objetivos para construir um estado futuro e gerenciar todo o portfólio continuamente durante o processo [5]. De acordo com o Gartner, a AE está mais voltada a uma estratégia do que uma disciplina de engenharia que é usada para construir uma visão consolidada da empresa alinhada com as necessidades de negócios de uma organização [8].

Princípios de Arquitetura Empresarial. The Open Group [30] define princípios de arquitetura como "regras e diretrizes gerais subjacentes para o uso e implantação de todos os recursos e ativos de TI na empresa. Eles refletem um nível de consenso entre os vários elementos da empresa e formam a base para a tomada de decisões de TI futuras".

De acordo com Kempegowda e Chaczko [15], os princípios assistem na obtenção da visão da organização e na validação dos resultados e dão à equipe o poder de decisão durante a execução do framework de AE. Com o aumento significativo de tecnologias como Cloud, Big Data, Social Media, Internet of Things, Robotic Process Automation

(RPA), Analytics, dentre outras, é crítico definir princípios que são de fácil entendimento, amplos e práticos de se usar [15]. Princípios de arquitetura são amplamente produzidos, aceitos e valorizados, no entanto, não são largamente aprovados e efetivamente usados por arquitetos empresariais, designers, desenvolvedores, CIOs e gerentes [23].

O The Open Group Architecrure Framework (TOGAF) vem mostrando grande aceitação nas organizações [15], sendo que, neste presente trabalho, os 21 princípios definidos pelo TOGAF foram usados para desenvolver um modelo de decisão para avaliar os impactos das tecnologias de transformação digital (Indústria 4.0) sob os princípios de arquitetura propostos pelo TOGAF. A versão atual 9.2, lançada em 2018, contém os mesmos princípios da versão 9.0, lançada em 2009.

2.2 Transformação Digital

Transformação digital é definida como "o uso de tecnologia para melhorar radicalmente a performance ou alcance das empresas" [34]. Outra definição conhecida do termo é a que "é atingida quando os usos digitais que vem sendo desenvolvidos possibilitam inovação e criatividade e estimulam mudanças dentro do domínio profissional ou do conhecimento" [20].

O termo Indústria 4.0 (I4.0), foi mencionado pela primeira vez na feira de Hannover em 2001. Lu [18] sumariza indústria 4.0 como um processo de produção integrado, adaptado, otimizado, orientado ao serviço e interoperável, que está correlacionado com algoritmos, big data, e grandes tecnologias. A I4.0 facilita a interconexão e a informatização da indústria tradicional. De acordo com Liao et al. [17] as tecnologias de modelagem e virtualização/visualização vem sendo as duas tecnologias de habilitação mais frequentes aplicadas na implementação da Industria 4.0. Os objetivos da Indústria 4.0 são os de promover uma customização habilitada para TI dos produtos produzidos; de realizar uma adaptação automática e flexível da cadeia de produção; de rastrear partes e produtos; de facilitar a comunicação entre partes, produtos e maquinas; de aplicar paradigmas de interação homem-máquina (HMI); de alcançar a otimização de produção habilitada para IoT em *smart factories*; e o de promover novos tipos de serviços e modelos de negócios de interação na cadeia de valor.

2.3 Métodos Multi-Critérios De Tomada De Decisão

De acordo com a Sociedade Internacional de Métodos Multicritério de tomada de Decisão, "Métodos Multicritério de tomada de Decisão (MCDM) é o estudo de métodos e procedimentos pelos quais as preocupações sobre múltiplos critérios conflitantes podem ser formalmente incorporadas no processo de planejamento de gestão" [14]. De acordo com Cestari et al. [9], um MCDM ajuda os decisores a entender suas preferencias, utilizando critérios para escolher a alternativa adequada ou priorizar e ranquear um conjunto de alternativas. Ao estruturar o processo de decisão é essencial entender o tipo de problema no qual a decisão está inserida. O tipo de problema guiará a escolha do método multicritério a ser utilizado. Dito isso, o método que mais se adapta aos requisitos de avaliação desta pesquisa é o PROMETHEE.

O PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) é um método multicritério desenvolvido por Brans et al. [6,7]. É um método de ranqueamento com concepção e aplicação simples se comparado com outros métodos multicritério. Este método se adapta bem a problemas onde um número finito de alternativas deve ser ranqueado de acordo com múltiplos critérios, que podem vir a ser conflitantes [2]. A tabela de avaliação é o ponto de partida do PROMETHEE, nesta tabela as alternativas são avaliadas sob diferentes critérios. A implementação do PROMETHEE necessita de dois tipos adicionais de informação, sendo eles: (1) Informação sob a relativa importância, ou seja, os pesos dos critérios considerados. (2) Informação sobre a função de preferência do decisor, que ele/ela usa ao comparar a contribuição das alternativas em termos de cada critério.

3 ESTRATÉGIA DE PESQUISA

3.1 Levantamento das principais tecnologias no contexto de AE

A fim de identificar as principais tecnologias da I4.0, uma revisão de literatura foi realizada. De acordo com Xiao e Watson [35], a revisão de literatura é uma característica essencial da pesquisa acadêmica. O avanço do conhecimento deve se basear em trabalhos existentes. Ao revisar a literatura relevante, entendemos a amplitude e a profundidade do corpo de trabalho existente e identificamos lacunas a serem exploradas.

Com o intuito de identificar as principais tecnologias de transformação digital aplicadas ao âmbito da arquitetura empresarial, uma revisão da literatura foi realizada. Primeiramente foram identificadas as palavras-chave que seriam aplicadas na pesquisa. O “eixo 1” contempla as palavras referentes ao universo de avaliação do espaço problema enquanto o “eixo 2” abrange palavras pertinentes ao segundo espaço de avaliação. As palavras-chave utilizadas na pesquisa estão presentes no Tabela 1.

Tabela 1. Palavras-Chave

Eixos / Operador Booleano	**Palavras-Chave**
Eixo 1	"Enterprise Architecture" OR "TOGAF"
Operador Booleano entre os eixos	AND
Eixo 2	"Technologies" OR "Digital Transformation Technologies"

Uma vez que as palavras-chaves foram reconhecidas, os critérios de pesquisa foram definidos: (i) pesquisa avançada, de 2016 a 2020; (ii) seleção de textos disponíveis em inglês e (iii) exclusão de textos que não contemplam o nome do autor. Uma busca com as palavras-chave foi realizada na base SCOPUS, gerando um resultado de 1531 artigos. Após a aplicação dos critérios de pesquisa citados acima 505 artigos permaneceram. Em seguida uma série de análises foram realizadas e como resultado,

32 artigos restaram. A Tabela 2 contempla os critérios de pesquisa aplicados na seleção dos artigos.

Tabela 2. Critérios de Pesquisa

Critérios de Pesquisa	**Resultados**
Limitados aos últimos 5 anos, ou seja, 2020,2019,2018,2017 e 2016.	557
Limitados à língua inglesa.	540
Exclusão de artigos que não possuem nome do autor	505
Análise de títulos	89
Análise de abstracts	34
Artigos disponíveis	32

Com os 32 artigos restantes, foi utilizado o software NVivo [25] no qual foi aplicada a ferramenta "word-count" para determinar as tecnologias mais mencionadas. Uma análise de cluster (Fig. 1) das palavras encontradas, foi gerada.

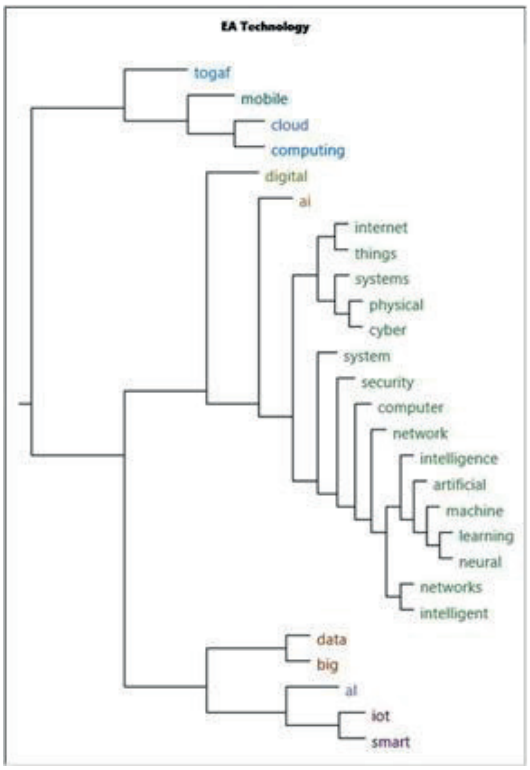

Fig. 1. – Análise de Cluster

Ao analisar os resultados gerados, cinco principais tecnologias no âmbito de I4.0 e AE foram identificadas: Cloud Computing, Internet of Things (IoT), Artificial Intelligence (AI), Big Data e Cyber-Physical Systems. O Tabela 3 contempla as tecnologias e suas respectivas descrições.

Tabela 3. Principais Tecnologias (Alternativas)

Tecnologias	Definição
Artificial Intelligence (AI)	Artificial Intelligence (AI) é o domínio da ciência e engenharia relacionado as teorias e práticas de desenvolvimento de sistemas que exibem características comumente associadas à inteligência de comportamento humano, como percepção, processamento de linguagem nativa, resolução de problemas e planejamento, aprendizado e adaptação e, atuação no meio ambiente. Seu principal objetivo científico é o entendimento dos princípios que possibilitam o comportamento inteligente em humanos, animais e agentes artificiais [29].
Big Data	Big Data é o desenvolvimento tecnológico na área de armazenamento e processamento de dados que oferecem a possibilidade de lidar com os aumentos exponenciais nos volumes de dados apresentados em qualquer formato em períodos cada vez menores [27].
Cloud Computing	A computação em nuvem é uma tecnologia em evolução que está constantemente gerando impacto no setor de TI. Ele executa todas as tarefas computacionais pela Internet usando técnicas de virtualização e permanece isolado de intrincadas vastas infraestruturas de hardware e software [1].
Cyber-Physical Systems	Sistemas ciberfísicos (CPS) São sistemas de entidades computacionais colaborativos que apresentam uma conexão intensa com o mundo físico circundante e seus processos em andamento, fornecendo e utilizando, ao mesmo tempo, serviços de acesso a dados e processamento de dados disponíveis na Internet [21].
	A IoT integra diversas tecnologias para transmitir informações de fontes que não são apenas pessoas (através de seus dispositivos tradicionais: laptop, desktop, celulares e similares), mas também objetos reais e virtualizados que fazem parte do

Internet of Things (IoT)	ambiente em que o serviço é entregue aos usuários. Outro aspecto é que esses dados não devem apenas estar disponíveis para um determinado aplicativo, mas devem se tornar uma espécie de base informativa comum, para que diferentes aplicativos possam compartilhar livremente e em escala global as fontes dessas informações devidamente organizadas na forma de uma rede genérica [4].

4 Resultados

Através da utilização do método PROMETHEE foi possível realizar uma avaliação das tecnologias, de maneira a determinar as que possuem maior influência sobre cada um dos critérios. Esta comparação entre as tecnologias foi realizada através da utilização de uma função de preferência e de um peso escolhido para cada critério. Neste artigo, os pesos dos critérios foram iguais para todos, sendo ele igual a 1. A função de preferência adotada foi a função Usual.

Os critérios escolhidos para a avaliação foram os 21 princípios de arquitetura do TOGAF (Tabela 4), já as alternativas utilizadas foram as tecnologias obtidas através da revisão de literatura realizada nesta pesquisa (Tabela 3). Tais critérios e alternativas foram escolhidos a fim de elaborar um modelo de decisão para avaliar as tecnologias de transformação digital(Indústria 4.0) mais impactantes sobre os princípios de arquitetura propostos pelo TOGAF.

Tabela 4. Princípios de Arquitetura TOGAF (Critérios)

Número	Princípios de Arquitetura TOGAF
1	Primazia dos Princípios
2	Maximizar os Benefícios para a Empresa
3	Gestão de Informação é Negócio de Todos
4	Continuidade de Negócios
5	Aplicativos de Uso Comum
6	Orientação de Serviço
7	Conformidade com a Lei
8	Responsabilidade de TI
9	Proteção da Propriedade Intelectual
10	Informações tratadas como Ativo
11	Informações Compartilhadas

12	Informações Acessíveis
13	Administrador de Dados
14	Terminologia Comum e Definição de Dados
15	Segurança da Informação
16	Independência Tecnológica
17	Facilidade de Uso
18	Mudanças com Base em Requisitos
19	Gerenciamento Sensível a Mudança
20	Controle de Diversidade Técnica
21	Interoperabilidade

Com estas informações em mãos, iniciou-se a criação do modelo de avaliação no software VISUAL PROMETHEE [33]. Além dos atributos já mencionados foi necessário escolher como as alternativas seriam avaliadas para cada critério. No campo "Min/Max" optou-se pelo Máximo, ou seja, quanto maior o desempenho da alternativa naquele critério maior a influência daquela tecnologia para o mesmo. Já a escala utilizada na avaliação foi a escala qualitativa 5-point, variando nos seguintes níveis de influência: 0 (sem influência), 1 (influência baixa), 2 (influência média), 3 (influência alta) e 4 (influência muito alta), respectivamente. O modelo devidamente estruturado no software está presente na Fig. 2.

Principios x Tecnol...	Primazia dos ...	Maximize Be...	Gestão da In...	Continuidad...	Aplicativos d...	Orientação d...	Conformidad...	Responsabili...	Proteção da ...	Informações...
Unit	5-point	5-point	5-point	5-point	5-point	5-point	5-point	5-point	5-point	5-point
Cluster/Group	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
Preferences										
Min/Max	max	max	max	max	max	max	max	max	max	max
Weight	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Preference Fn.	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual	Usual
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
- P: Preference	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Statistics										
Minimum	0,0	4,0	0,0	3,0	2,0	2,0	1,0	3,0	2,0	3,0
Maximum	0,0	4,0	3,0	4,0	3,0	3,0	2,0	4,0	3,0	4,0
Average	0,0	4,0	1,6	3,6	2,8	2,6	1,6	3,6	2,6	3,4
Standard Dev.	0,0	0,0	1,4	0,5	0,4	0,5	0,5	0,5	0,5	0,5
Evaluations										
AI	No influence	Very high	No influence	Very high	Medium	Medium	Medium	High influence	Medium	High influence
Big Data	No influence	Very high	High influence	Very high	High influence	High influence	Medium	Very high	High influence	Very high
Cloud Computing	No influence	Very high	High influence	Very high	High influence	High influence	Medium	Very high	High influence	Very high
Cyber-Physical S...	No influence	Very high	No influence	High influence	High influence	High influence	Low influence	High influence	Medium	High influence
IoT	No influence	Very high	Medium	High influence	High influence	Medium	Low influence	Very high	High influence	High influence

Fig. 2. Estrutura do Método PROMETHEE

Para cada alternativa, dois índices são calculados: o fluxo positivo (Φ+) que representa o quanto uma certa alternativa é melhor que as outras e o fluxo negativo (Φ-), que

expressa o quanto uma alternativa é superada pelas demais [28]. Com a aplicação dos dados foram gerados os valores de "Phi" para cada uma das tecnologias através do software, ou seja, foram gerados os índices de fluxo positivo, negativo e o fluxo total de cada alternativa (Fig. 3).

Rank	action	Phi	Phi+	Phi-
1	Big Data	0,3095	0,3929	0,0833
2	Cloud Computing	0,2738	0,3810	0,1071
3	IoT	0,0833	0,3095	0,2262
4	AI	-0,1905	0,2262	0,4167
5	Cyber-Physical Systems	-0,4762	0,0357	0,5119

Fig. 3. Valores de "Phi" gerados pelo PROMETHEE

Percebe-se que o fluxo total de Big Data, Cloud Computing e IoT é positivo, já os fluxos de AI e Cyber-Physical Systems são negativos. A Fig. 4 apresenta o fluxo resultante, baseado no PROMETHEE, promovendo assim uma representação gráfica do resultado obtido.

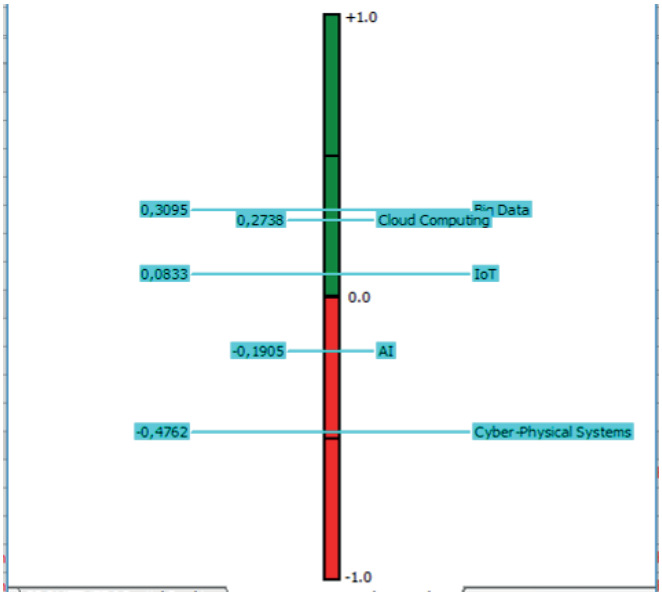

Fig. 4. Resultado gerado pelo PROMETHEE

Por meio da aplicação do modelo decisional foi possível determinar que a tecnologia com maior impacto nos princípios de arquitetura do TOGAF é a Big Data, seguida pelo Cloud Computing, com fluxos de 0,31 e 0,27 respectivamente.

5 Conclusão

O presente trabalho teve como objetivo aplicar um modelo de decisão para avaliar os impactos das tecnologias de transformação digital sob os princípios de arquitetura propostos pelo TOGAF. Para tal, primeiramente uma revisão de literatura for realizada a fim de identificar as principais tecnologias de transformação digital utilizadas no âmbito da arquitetura empresarial. Em seguida, o modelo decisional foi desenvolvido baseado no método multicritério de tomada de decisão PROMETHEE, auxiliando decisores a tomarem decisões mais assertivas, reduzindo riscos e impactos negativos que podem afetar a organização como um todo. Os 21 princípios de arquitetura apresentados pelo TOGAF foram definidos como critérios a serem utilizados na avaliação. Por fim, o modelo foi aplicado e como resultado apontou as tecnologias Big Data e Cloud Computing como as que geram maior efeito sob os princípios analisados.

Ambas as tecnologias têm sido altamente abordadas no âmbito acadêmico e aplicadas em organizações. Segundo Malik, Rashid e Wani [19], Cloud Computing elimina a necessidade de ter uma infraestrutura completa de software e hardware para atender aos requisitos e aplicativos dos clientes. Com isso princípios como: Aplicativos de Uso Comum; Independência Tecnológica; Facilidade de Uso; Controle de Diversidade Técnica, são diretamente impactados pelo uso dessa tecnologia.

De acordo com um estudo realizado por Chen e Zhang [10], os autores afirmam que 51% das empresas avaliadas acreditam que Big Data pode impactar no aumento da eficiência operacional e que 36% das organizações presumem que essa tecnologia pode auxiliar no direcionamento estratégico das empresas. Dito isso, dois princípios propostos pelo TOGAF são impactados: Maximizar os Benefícios para a Empresa; e Gerenciamento Sensível a Mudança. Big Data também trata os princípios que envolvem o gerenciamento de dados como: Gestão de Informação é Negócio de Todos; Informações tratadas como Ativo; Informações Compartilhadas; Informações Acessíveis; Terminologia Comum e Definição de Dados; e Segurança da Informação.

A fim de aprimorar o estudo realizado, propõe-se como trabalho futuro, detalhar as tecnologias encontradas. Isso acarretará uma avaliação mais assertiva e auxiliará no direcionamento de oportunidades de evolução e transformação das organizações com tecnologia.

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El gasto energético y la eficiencia energética en los hogares en Argentina

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Resumen. Las políticas de eficiencia energética (EE) son sumamente relevantes para alcanzar los compromisos de mitigación del cambio climático asumidos por Argentina. Para lograr un buen diseño e implementación de estas políticas es necesario analizar el gasto energético de los hogares, ya que la mejora de la EE podría aliviar los presupuestos familiares. En este contexto, el objetivo del presente trabajo es analizar de manera exploratoria cómo se distribuye el gasto energético de los hogares de Argentina en 2017-2018 por regiones y según clima educativo, y discutir la importancia de estudiar el comportamiento de esta distribución para diseñar e implementar políticas de EE. Para ello se utilizan los microdatos provenientes de ENGHo 2017-2018. Los resultados parecen evidenciar una relación inversa entre el nivel educativo del hogar y la participación del gasto energético sobre el gasto total. Esto podría indicar que es necesario formular políticas de EE especialmente dirigidas a los hogares más vulnerables.

Palabras clave: Gasto energético, Hogares, Eficiencia Energética.

1 Introducción

En un contexto de aumento de las emisiones antropogénicas de Gases de Efecto Invernadero (GEI), la Eficiencia Energética (EE) adquiere un rol preponderante. Mejorar la EE implica promover un aumento de los usos energéticos para un nivel dado de energía o bien la disminución de la cantidad de energía para satisfacer un nivel dado de usos (IEA, 2014).

A nivel mundial, en el año 2015, se firma el Acuerdo de París en la 21ª Conferencia de las Partes (COP) de la Convención Marco de Naciones Unidas sobre Cambio Climático (CMNUCC) con el objetivo de mantener el aumento de la temperatura media mundial muy por debajo de 2ºC con respecto a los niveles preindustriales. En el caso de Argentina, en el año 2016 se ratifica la firma del Acuerdo mediante la Ley 27.270 y en su Contribución Nacional Determinada (NDC por sus siglas en inglés) en la que se compromete a no exceder la emisión neta de 483 millones de toneladas de

dióxido de carbono equivalente (tCO2eq) en el año 2030. En el año 2017, se lanzó el Plan de Acción Nacional de Energía y Cambio Climático, contemplando como uno de los ejes centrales a la EE en distintos sectores de consumo final, incluyendo al sector residencial (MADS y MEM, 2017).

En Argentina, para evaluar la EE y mejorar su implementación en los hogares lo ideal es contar con un análisis microeconómico. Este análisis permite conocer cómo toman los hogares (y personas) las decisiones de consumo de energía e inversión en EE. Si se estudian dichos determinantes se pueden conocer los impulsores y las barreras a la EE y, de esta manera, se facilita el diseño de instrumentos de política.

En este contexto, el objetivo del presente trabajo es analizar de manera exploratoria cómo se distribuye el gasto energético de los hogares de Argentina para el periodo 2017-2018 por regiones y según clima educativo, y discutir la importancia de estudiar el comportamiento de esta distribución para diseñar e implementar políticas de EE. Para cumplimentar el objetivo, se realizará un análisis estadístico descriptivo a partir de los microdatos provenientes de la Encuesta Nacional de Gastos de los Hogares (ENGHo) y una revisión bibliográfica de la literatura existente.

2 Revisión de antecedentes en el estudio del gasto energético

En Argentina no existen antecedentes que estudien los determinantes del gasto energético de los hogares. Sin embargo, se encuentran diversos estudios que estiman la demanda de energía en el sector residencial, aunque sólo unos pocos utilizan microdatos en su análisis. Entre estos últimos se puede mencionar un grupo de trabajos que sin ser específicos del gasto energético, lo incluyen en su análisis. Marchionni et al. (2008) analizan la incidencia distributiva del gasto y consumo de servicios públicos, incluyendo electricidad y gas natural. Lakner et al. (2016) analizan la incidencia distributiva de los subsidios a los servicios públicos, incluyendo la energía.

Luego, otro grupo de trabajos estudia específicamente temáticas de energía. Margulis (2014) analiza la demanda residencial de electricidad en función de variables, tales como el ingreso y la cantidad de miembros del hogar, acceso a la red de gas natural y el precio en cada jurisdicción. Hancevic y Navajas (2015) evalúan el consumo de electricidad de los hogares según sus características socioeconómicas, de equipamiento y localización y lo vinculan con cuestiones de EE. Los autores encuentran que la falta de acceso al gas natural deriva en ineficiencias en el consumo de electricidad. Chévez et al. (2018) presentan un análisis del consumo eléctrico residencial a nivel territorial, encontrando que las mayores demandas eléctricas se presentan en regiones cálidas y que la mayor demanda de electricidad está asociada a un mayor nivel de equipamiento en los hogares.

3 Explorando el gasto energético en Argentina: ENGHo 2017-2018

El relevamiento de la ENGHo 2017-2018 se llevó a cabo entre noviembre de 2017 y noviembre de 2018, con el objetivo de obtener información acerca de los gastos y los ingresos de los hogares y sus características sociodemográficas (INDEC, 2019). Para ello, los bienes y servicios se agrupan en 12 divisiones según las necesidades que satisfacen. En este trabajo, el foco del análisis estará en la división denominada "Vivienda, agua, electricidad, gas y otros combustibles". En concreto, esta división representó el 14,5% del gasto de consumo para el total del país y la subdivisión específica de "Electricidad, gas y otros combustibles" representó un 5,9%.

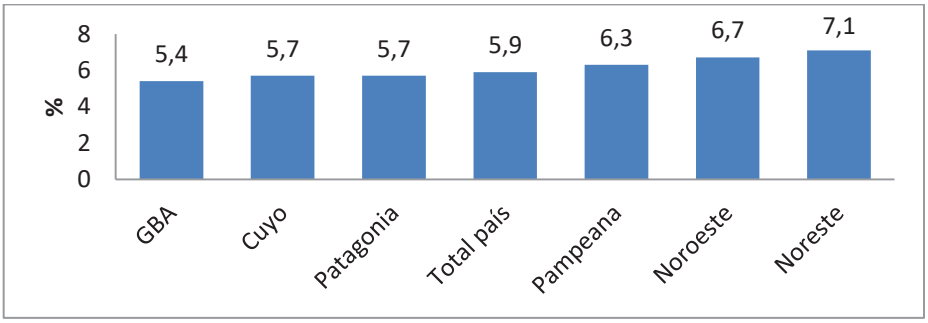

Fig. 1. Porcentaje del gasto en Electricidad, gas y otros combustibles según regiones 2017-2018. Fuente: elaboración propia en base a datos de INDEC

En la Fig. 1 se puede observar que las regiones de GBA, Cuyo y Patagonia poseen una menor participación del gasto energético en el gasto total de los hogares con respecto al total del país. Esto podría estar vinculado a los esquemas tarifarios regionales y a la existencia de subsidios.

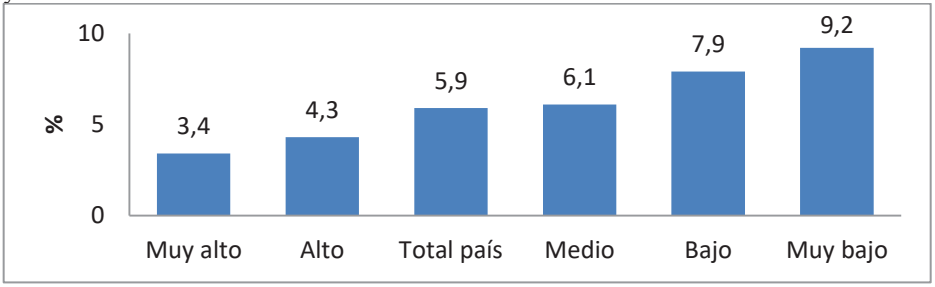

Fig. 2. Porcentaje del gasto en Electricidad, gas y otros combustibles según clima educativo del hogar 2017-2018. Fuente: elaboración propia en base a datos de INDEC

En la Fig. 2 se muestra la participación del gasto energético sobre el total por clima educativo del hogar[1]. Esto parece evidenciar una relación inversa entre las variables.

[1] El clima educativo en años de escolaridad: menor a 7 es muy bajo, desde 7 y menor a 11 es bajo, desde 11 y menor a 14 es medio, desde 14 y menor a 16 es alto, y mayor a 16 es muy alto (INDEC, 2019).

Aunque la significatividad de dicha relación debe ser evaluada con un abordaje econométrico.

4 Discusión y Conclusiones

Los resultados preliminares del análisis estadístico exploratorio indican que existen diferencias a nivel regional que podrían estar vinculadas con los distintos esquemas tarifarios de energía, aunque también puede relacionarse con el hecho de que algunas regiones poseen un mayor nivel de desarrollo económico y por lo tanto la población cuenta con mejores condiciones de vida. Asimismo, parece existir una relación inversa entre el nivel educativo del hogar y la participación del gasto energético sobre el gasto total. Esto podría indicar que es necesario formular políticas de EE especialmente dirigidas a los hogares más vulnerables, para mejorar no solo la EE sino la asequibilidad de la energía. Por último, se destaca la importancia de analizar el gasto en energía cuando se desea mejorar EE. Comprender los factores que determinan el gasto energético y sus interrelaciones puede contribuir a equilibrar el dilema entre satisfacer las necesidades básicas de los hogares y reducir el impacto ambiental (Jiménez y García, 2017). Además, las políticas de EE para el sector residencial pueden tener impactos significativos no solo para el consumo energético sino también en gastos relacionados, aliviando los presupuestos familiares (Op.Cit.).

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A branch-and-bound method to minimize the total flow time in a permutation flow shop with blocking and setup times

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Abstract. This paper presents an improvement of the branch-and-bound algorithm for the blocking-in-process and setup times permutation flow shop problem with total flow time criterion, which is known to be NP-Hard for m≥2. For that, a new machine-based lower bound which exploits the machine idleness and the occurrence of blocking is proposed. Computational experiments were performed using a database that contains 27 classes of problems, varying the number of jobs (n) and the number of machines (m). Results show that the algorithm can handle most of the n<20 problems in less than one hour. Therefore, this work can support the scheduling of many applications in manufacturing systems with limited buffers and setup times.

Keywords: Scheduling, Permutation flow shop, Blocking, Setup, Total flow time, Branch-and-bound.

1 Introduction

In the permutation flow shop scheduling problem, *n* jobs must be processed on each of the machines in the same order. It is also assumed that every job has the same processing sequence on every machine, each machine can process at most a single job and no interruptions are allowed. The processing time of each job on each machine is given. The total flow time objective measures the time the jobs stay inside the system, and its minimization results in cost reductions related to initial inventory and in-process maintenance costs. For $m \geq 2$, the flow shop with total flow time criterion problem is NP-hard [1].

Many papers considered the problem with unlimited buffers [2] or considering the setup time embedded in the processing time of the job [3], [4] and [5]. In this paper, the setup time is separated from the processing time, allowing a machine to be prepared to initiate the processing of a job before the previous machine has finished processing this job. This ensures better flexibility for scheduling, allowing for a better use of time, hence a possible reduction in the makespan. Furthermore, the setup time depends on the sequence of jobs, as well as the machine. In other words, there is a different setup time for each pair of jobs in each machine.

In an environment with blocking, there are limited buffers in between the machines. In this paper, a zero buffer constraint is considered, i.e., if machine k finishes the processing of job j and machine k+1 is not able to receive the job (because it is still processing job j-1 or is still being set up), the job remains on machine k, blocking it. In this case machine k is unable to receive the next job of the sequence. The absence of buffers can cause the occurrence of blocking, which is when a job completed on a specific machine blocks it until the following one is ready for processing. Another reason for the occurrence of blocking lies in the production technology itself [6]. For instance, in robotic cells, a machine may be blocked while waiting for the robot arm to pick up the finished job and move it to the next stage [7].The flow shop problem with zero buffer can be used to model any flow shop problem with limited buffer because a unit capacity buffer can be represented by a machine with zero processing time for all jobs [3]. Fig. 1 shows an example of the problem in a Gantt chart.

In Fig. 1 is shown the moment when job i just finished being processed by both Machine 1 and 2. Thus, both machines begin by being setup to start processing job j (S_{ij1} and S_{ij2}). It can be noted that Machine 2 must wait for Machine 1 to finish processing job j before it can start processing it, so it stays idle for a while. Right after finishing processing job j each machine can start setting up for the next job ($S_{j,j+1,1}$ and $S_{j,j+1,2}$). In this case, notice that Machine 1 finished processing job j+1 before Machine 2 had finished the setup process. Therefore, a *block* occurs, preventing Machine 1 from starting to setup for the next job.

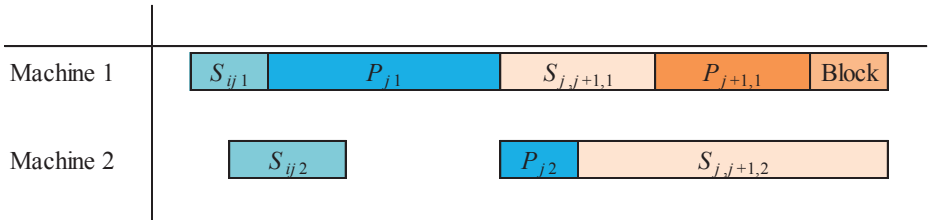

Fig. 1. Example of a blocking flow shop scheduling problem with setup times

Because of its complexity, large-size blocking flow shop problems are usually solved by heuristics. [8] are among the first authors that explored the blocking environment. Their work consisted of reducing the 2-machine flow shop with zero buffer and makespan minimization to a special case of the Traveling Salesman Problem, which can be solved in polynomial time using the Gilmore-Gomory algorithm [9]. [3]

developed the Profile Fitting constructive heuristic, which fits an unscheduled job that provides the least blocking and machine idle time in front of a partial sequence.
[10] developed a two-machine case branch-and-bound to minimize the mean completion time and a three-machine case for makespan on a flow shop environment. [11] extended this machine based lower bound to m machines when the objective is minimizing the sum of completion times, or total flow time when all release dates are zero. [12] developed a machine based lower bound with the preemptive relaxation, which dominated the formulation of [11] in terms of value. [13] proposed a new total flow time lower bound for flow shop that dominated both previous formulations. The results point out that the algorithm can easily handle $n \leq 15$ and can solve most of $15 < n \leq 20$ problems.
A reduced number of papers explores the blocking flow shop solved by a branch-and-bound algorithm. [14] presented a branch-and-bound algorithm for flow shops with zero buffer. The authors developed a departure time based lower bound that was used for the total tardiness and makespan objectives. [15] outperformed the lower bound for flow shop with blocking in order to minimize makespan proposed by [14] in 85.2% of the cases. Their lower bound calculated an underestimate departure time of the last job in non-partial sequence. [16] developed a lower bound for flow shop with zero buffer constraint with the total flow time criterion. The algorithm solved $n \leq 18$ and $m \leq 10$ problems and 17 instances of Taillards benchmark [17] in less than 20 minutes. [18] proposed an initial upper bound (UB) to reduce the computational time of the branch-and-bound algorithm. The initial UB was provided by a constructive heuristic, and a significant reduction of the computational time was noticed.
Just a few papers addressed the blocking with setup times in flow shop. [19] were one of the first to explore this problem. They adapted the lower bound presented by [10]. [20] was the first paper to address the use of a branch-and-bound algorithm for the problem. A lower bound was developed for the makespan in a flow shop with blocking and sequence dependent setup times, addressing two structural properties of the problem: an upper bound for the machine idle and a lower bound for the machine blocking time.
In this article a lower bound for the branch-and-bound algorithm for blocking with setup time permutation flow shop problems with total flow time criterion is presented, in order to optimally solve small and medium size problems. In Section 2 the problem is defined, and some basic calculations are shown. The branch-and-bound algorithm and the lower bound development are presented in Section 3. The computational tests are showed in Section 4 and the conclusions are presented in Section 5.

2 Problem Definition

The flow shop problem with blocking and setup can be defined by the following set of equations. Let σ={1, 2, …, i, j, …, n} be an arbitrary sequence of jobs, k={1, 2, …, m} be the sequence of available machines, *i* be the job that directly precedes job *j* in the sequence, P_{jk} be the processing time of the *j*-th job in the sequence on machine *k*, S_{ijk} be the setup time of machine *k* between the *i*-th and the *j*-th job in the sequence, S_{01k}

be the setup time of machine k before processing the first job in the sequence, R_{jk} be the completion time of the setup of machine k to the j-th job in the sequence and D_{jk} be the departure time of the j-th job in the sequence on machine k. Equations 1 to 5 show how the departure times are calculated for a given sequence:

$$R_{1k} = S_{01k} \; \forall 1 \leq k \leq m \tag{1}$$

$$D_{j1} = \max\left(R_{j2}, R_{j1} + P_{j1}\right) \; \forall 1 \leq j \leq n \tag{2}$$

$$D_{jk} = \max\left(R_{j,k+1}, D_{j,k-1} + P_{jk}\right) \; \forall 1 \leq j \leq n; 2 \leq k \leq m-1 \tag{3}$$

$$D_{jm} = D_{j,m-1} + P_{jm} \; \forall 1 \leq j \leq n \tag{4}$$

$$R_{jk} = D_{ik} + S_{ijk} \; \forall 2 \leq j \leq n; 1 \leq k \leq m \tag{5}$$

Initially, the setup completion times of the machines for the first job in the sequence are calculated by Equation 1. Then, the departure times of the first job in all machines are calculated by Equations 2, 3, and 4. Then, Equation 5 is used to calculate the setup completion time of all machines for the following job. Equations 2, 3, and 4 are used again to calculate the departure times of the following job in all machines. The total flow time is the sum of all departure times of all jobs on the last machine. Therefore, Equation 6 is used to calculate the total flow time.

$$TFT = \sum_{j=1}^{n} D_{jm} \tag{6}$$

3 The Branch-and-Bound Algorithm

The branch-and-bound algorithm branches an original high complexity problem in two or more sub-problems, called nodes, that are easier to solve. This process can be done recursively until a feasible solution is obtained. The nodes are defined by an exclusive sub-sequence which is called Partial Sequence (PS). The set of jobs not included in PS is called Non-Partial Sequence (NPS).

When a node is branched, one or more partial sequences (nodes) are created by adding up a new job from |NPS| to the partial sequence associated with the branched node. The search tree is created using the depth first rule, in which the node with more jobs in the PS is branched. The ties are broken by the minimum lower bound. For each node, a lower bound of the total flow time is computed and this node is fathomed if the incumbent solution is smaller than its lower bound. As the focus of this article is to evaluate the tightness of the proposed lower bound, the initial incumbent solution is set to a very high value and is updated every time a better feasible solution is reached.

3.1 Proposed Lower Bound

The effectiveness of a branch-and-bound algorithm is heavily related to the lower bounds used. Such bounds are more useful if their computational complexities are small and if they are tight. The proposed lower bound assumes a relaxation in which one

machine can process one job at a time and the others can handle the whole set of n jobs at a time. Since the SPT rule is optimal for total flow time criterion on a single machine [21], it is possible to obtain a lower bound for the flow shop problem. The lower bound considering a partial sequence σ of size s is computed as follows:

$$LB = TFT(\sigma) + \max_{1 \le k \le m} LB_k \tag{7}$$

$$LB_k = \sum_{t=s+1}^{n} (ED_{tk} + \sum_{r=k+1}^{m} p_{tr}) \tag{8}$$

In which ED_{tk} is the underestimate of the departure time of a job in position $t > s$ on machine k, as shown in Equation 9. Where *s* is the last job in σ and $p_{[j],k}$ is the (s-j)-th smaller processing time on machine k.

$$ED_{tk} = max\left(max\left(D_{sk} + \sum_{j=s+1}^{t-1} p_{[j]k}\,; D_{s,k+1} + \sum_{j=s+1}^{t-2} p_{[j],k+1} + Setup_{k+1}(t-1)\right) + Setup_k(t); D_{s,k-1} + \sum_{j=s+1}^{t} p_{[j],k-1}\right) + p_{[t]k} \tag{9}$$

For $k = 1$ and $k = m$, the formulation excludes the $k - 1$ and $k + 1$ terms, respectively.

4 Computational Results

This section describes the computational tests done in order to evaluate the effectiveness of the proposed lower bound (LB) when applied to a branch-and-bound algorithm. The experimentation used the problem instances database from [14], in which the processing times were randomly generated in a uniform distribution ranging from 1 to 99. The database consists of 27 different problem sizes, with 20 unique problems each, totaling 540 instances.
The database provided by [15] does not include setup times. Therefore, in order to analyze the influence of the setup times in the algorithm, four different setup time databases were generated for these tests. To create these databases, the values were uniformly distributed between:

- Database 1: 01 and 09;
- Database 2: 01 and 49;
- Database 3: 01 and 99;
- Database 4: 01 and 124;

The setup data ranges were defined to approximately: 10%; 50%; 100%; and 150% of the processing time. By doing so, it is possible to evaluate the influence of the setup time on the methods. If the results in problems where the setup time is 10% of the processing time and where the setup time is 150% of the processing time are similar, then it can be stated that the value of the setup time does not influence in which is the best method.
The processing time database was combined with each of the setup time database. Thus, a total of 2160 problems were analyzed.

The experimentation codes were written in C and ran on an Intel Core i7-8700K 3.7GHz, 16GB RAM DDR4 3000MHz using Microsoft Visual Studio Community 2017. The computational times were obtained through the function clock(). A time limit of 3600 seconds was set for the execution of the algorithm.
As no other lower bound for the $F_m|block, S_{ijk}|\sum C_{jm}$ was found in the literature, the tests were performed by comparing three variations of the proposed lower bound (LB). The purpose of the tests is to evaluate which variations of the LB solve the problems in a viable computational time. The three variations are:

- LB_1: $S_{i[1]k}$ and $S_{[1]jk}$ were defined as zero and were not included in the searches;
- LB_2: $Setup_k(j)$ was defined as zero and was not included in the searches;
- LB_3: LB was fully calculated.

To compare the performance of the lower bounds, the relative percentage deviation was calculated for the average number of created nodes and computational times, using the following equation:

$$RPD_{Variation} = \frac{\sigma_{Variation} - \sigma^*}{\sigma^*} * 100 \quad (10)$$

In Equation 10, $\sigma_{Variation}$ is the mean value of either the computational time or the number of created nodes obtained with the LB variation analyzed and σ^* is the best value obtained among all the LB variations.
Each problem was solved using all variations of the LB, and all algorithms were run in the same conditions. Tables 1, 2, 3, and 4 show the average CPU time spent, the average number of created nodes, and the number of unsolved problems considering database 1, 2, 3, and 4, respectively, for the setup times.

Table 1. Comparison of the variations of LB – Database 1

Size		Ave. Node Count			Ave. CPU Time (ms)			Number of Unsolved		
n	m	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3
10	2	581	576	**530**	0.01	**0.008**	0.01	**0**	**0**	**0**
10	3	8760	8510	**8390**	0.071	**0.06**	0.069	**0**	**0**	**0**
10	4	44300	40400	**40200**	0.293	**0.223**	0.28	**0**	**0**	**0**
10	5	382000	**381000**	382000	1.904	**1.722**	1.944	**0**	**0**	**0**
10	7	696000	**661000**	672000	3.28	**3.185**	3.398	**0**	**0**	**0**
10	10	**1560000**	1580000	1600000	**7.891**	8.873	8.768	**0**	**0**	**0**
12	2	2170	2180	**1930**	0.061	**0.043**	0.058	**0**	**0**	**0**
12	3	99500	82700	**81300**	0.84	**0.575**	0.689	**0**	**0**	**0**
12	4	5510000	5260000	**5210000**	26.32	**26.221**	28.437	**0**	**0**	**0**
12	5	13500000	**13200000**	13300000	66.189	**63.332**	67.047	**0**	**0**	**0**
12	7	41600000	41500000	**40900000**	223.579	**205.25**	224.6	**0**	**0**	**0**
12	10	90900000	**77800000**	79400000	539.634	**437.121**	490.666	**0**	**0**	**0**
14	2	16900	18100	**15100**	0.644	**0.456**	0.578	**0**	**0**	**0**
14	3	8360000	**2840000**	8130000	57.063	**21.574**	57.114	**0**	**0**	**0**
14	4	**73100000**	111000000	109000000	**427.835**	550.287	595.402	**1**	2	2
14	5	205000000	**193000000**	**193000000**	1191.026	**1076.282**	1129.617	3	**2**	3
14	7	299000000	307000000	**289000000**	2101.254	**1976.018**	2098.374	8	**7**	8
14	10	589000000	614000000	**575000000**	3510.736	**3495.732**	3511.206	**19**	**19**	**19**
16	2	104000	117000	**92200**	5.135	**3.696**	4.657	**0**	**0**	**0**
16	3	3460000	3530000	**3180000**	129.559	**89.907**	119.861	**0**	**0**	**0**
16	4	165000000	**141000000**	160000000	1105.745	**878.71**	1065.442	4	**3**	4
18	2	843000	1030000	**750000**	55.86	**40.276**	51.584	**0**	**0**	**0**
18	3	**27100000**	37800000	34600000	840.463	**711.829**	873.607	**0**	1	1
18	4	**204000000**	270000000	225000000	2410.37	**2313.624**	2359.329	**9**	10	**9**
20	2	6180000	7690000	**5380000**	495.834	**381.78**	452.126	**0**	**0**	**0**
20	3	72400000	62400000	**51000000**	2653.069	**2306.895**	2488.527	12	**9**	10
20	4	**256000000**	281000000	260000000	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
Average		76439526.33	80479313.56	**76138653.70**	720.54	**673.84**	712.35	2.81	**2.70**	2.81

Table 2. Comparison of the variations of LB – Database 2

Size		Ave. Node Count			Ave. CPU Time (ms)			Number of Unsolved		
n	m	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3
10	2	1420	1310	**1100**	0.028	**0.018**	0.02	**0**	**0**	**0**
10	3	20800	**19600**	24400	0.191	**0.152**	0.187	**0**	**0**	**0**
10	4	72100	48800	**45100**	0.544	**0.387**	0.432	**0**	**0**	**0**
10	5	**206000**	242000	214000	1.382	1.355	**1.333**	**0**	**0**	**0**
10	7	519000	**496000**	513000	3.305	**2.867**	3.095	**0**	**0**	**0**
10	10	1310000	**1200000**	1210000	**6.753**	6.917	7.048	**0**	**0**	**0**
12	2	12400	12900	**9590**	**0.183**	0.248	0.277	**0**	**0**	**0**
12	3	**703000**	821000	800000	5.097	4.963	**4.076**	**0**	**0**	**0**
12	4	4090000	**2430000**	2790000	29.105	**17.793**	21.131	**0**	**0**	**0**
12	5	**5250000**	6080000	6140000	39.324	**37.569**	41.504	**0**	**0**	**0**
12	7	**24600000**	25500000	25400000	147.206	**142.323**	153.871	**0**	**0**	**0**
12	10	64900000	51100000	**50300000**	447.156	**335.646**	359.675	**0**	**0**	**0**
14	2	69600	74100	**54900**	2.657	**1.658**	2.177	**0**	**0**	**0**
14	3	8220000	6020000	**5760000**	97.614	**70.584**	72.341	**0**	**0**	**0**
14	4	66200000	**32600000**	34200000	550.658	**300.324**	369.081	1	**0**	**0**
14	5	178000000	**135000000**	161000000	1312.986	**985.334**	1193.124	4	**2**	4
14	7	**302000000**	394000000	315000000	2661.016	2828.815	**2654.844**	**11**	**11**	**11**
14	10	484000000	484000000	**447000000**	3365.358	**3238.832**	3308.02	18	**16**	17
16	2	520000	595000	**407000**	27.855	**19.407**	22.54	**0**	**0**	**0**
16	3	42300000	33900000	**31400000**	724.443	**539.128**	646.615	2	**1**	**1**
16	4	262000000	198000000	**192000000**	2491.518	**1731.481**	1995.478	9	**7**	**7**
18	2	4530000	5420000	**3550000**	314.373	**221.093**	251.807	**0**	**0**	**0**
18	3	122000000	174000000	**113000000**	3171.886	**2801.018**	2947.936	15	**12**	14
18	4	120000000	150000000	**99800000**	3576.416	**3407.678**	3501.395	19	**16**	18
20	2	21800000	30700000	**18600000**	2053.918	**1574.208**	1736.984	3	**2**	**2**
20	3	59100000	86000000	**57200000**	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
20	4	297000000	280000000	**275000000**	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
Average		76645345.19	77713359.63	**68200707.04**	1045.59	**943.33**	981.30	4.52	**3.96**	4.22

Table 3. Comparison of the variations of LB – Database 3

Size		Ave. Node Count			Ave. CPU Time (ms)			Number of Unsolved		
n	m	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3
10	2	2350	2050	**1580**	0.039	0.032	**0.03**	**0**	**0**	**0**
10	3	25300	17200	**17100**	0.274	**0.177**	0.205	**0**	**0**	**0**
10	4	49500	49300	**38400**	0.542	**0.421**	0.446	**0**	**0**	**0**
10	5	153000	124000	**118000**	1.284	**0.973**	1.068	**0**	**0**	**0**
10	7	405000	296000	**293000**	2.272	**2.124**	2.431	**0**	**0**	**0**
10	10	**698000**	808000	771000	**4.728**	5.416	5.95	**0**	**0**	**0**
12	2	12000	11500	**8660**	0.317	**0.218**	0.26	**0**	**0**	**0**
12	3	255000	**200000**	250000	3.771	**2.31**	2.953	**0**	**0**	**0**
12	4	**603000**	748000	639000	10.668	**8.469**	9.621	**0**	**0**	**0**
12	5	3140000	**2330000**	2360000	35.531	**22.606**	27.407	**0**	**0**	**0**
12	7	11300000	11100000	**10700000**	97.695	**82.675**	90.788	**0**	**0**	**0**
12	10	33200000	**20600000**	22100000	266.644	**171.832**	218.601	**0**	**0**	**0**
14	2	76200	76200	**55600**	2.665	**1.983**	2.378	**0**	**0**	**0**
14	3	**1480000**	2290000	1590000	**36.153**	37.268	40.787	**0**	**0**	**0**
14	4	24100000	**10500000**	16500000	328.047	**162.731**	239.095	**0**	**0**	**0**
14	5	104000000	**46500000**	65900000	1052.792	**554.925**	795.59	2	**0**	1
14	7	**216000000**	223000000	219000000	2088.795	**1897.037**	2051.695	**7**	**7**	**7**
14	10	365000000	358000000	**337000000**	3335.304	**3050.372**	3238.649	15	**14**	**14**
16	2	1270000	1060000	**728000**	57.811	**33.615**	37.202	**0**	**0**	**0**
16	3	31500000	33000000	**28100000**	619.392	**455.64**	527.823	**1**	**1**	**1**
16	4	104000000	110000000	**92800000**	2197.687	**1757.055**	1922.422	**6**	**6**	7
18	2	3480000	4190000	**2640000**	253.645	**167.221**	196.373	**0**	**0**	**0**
18	3	61500000	89000000	**58100000**	3342.785	**2933.593**	3050.296	14	11	**10**
18	4	**140000000**	183000000	**140000000**	3600.001	**3546.032**	3592.311	20	**19**	**19**
20	2	21600000	30500000	**18600000**	2077.88	**1618.644**	1799.302	6	**1**	2
20	3	**62200000**	93400000	64100000	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
20	4	144000000	147000000	**125000000**	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
Average		49261087.04	50659342.59	**44718901.48**	985.80	**878.27**	927.91	4.11	**3.67**	3.74

Table 4. Comparison of the variations of LB – Database 4

Size		Ave. Node Count			Ave. CPU Time (ms)			Number of Unsolved		
n	m	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3
10	2	1860	1560	**1200**	0.033	**0.022**	0.024	**0**	**0**	**0**
10	3	13200	**11600**	17900	0.174	**0.156**	0.187	**0**	**0**	**0**
10	4	51900	52600	**40100**	0.524	**0.417**	0.419	**0**	**0**	**0**
10	5	111000	96500	**91900**	1.108	**0.834**	0.94	**0**	**0**	**0**
10	7	305000	**242000**	249000	2.849	**2.016**	2.415	**0**	**0**	**0**

10	10	691000	**526000**	554000	4.369	**4.197**	4.892	**0**	**0**	**0**
12	2	17000	16500	**11900**	**0.242**	0.318	0.341	**0**	**0**	**0**
12	3	168000	135000	**121000**	3.159	**2.036**	2.497	**0**	**0**	**0**
12	4	859000	646000	**593000**	10.668	**5.908**	8.88	**0**	**0**	**0**
12	5	1060000	**944000**	1260000	16.945	**9.8**	17.235	**0**	**0**	**0**
12	7	6850000	**6480000**	6530000	70.271	**57.843**	67.667	**0**	**0**	**0**
12	10	21100000	**17900000**	18400000	222.954	**164.728**	196.393	**0**	**0**	**0**
14	2	90300	95800	**65900**	1.999	**1.874**	2.691	**0**	**0**	**0**
14	3	4120000	3060000	**2000000**	62.388	43.66	**41.695**	**0**	**0**	**0**
14	4	**26700000**	43300000	31200000	361.938	401.366	**358.702**	**0**	**0**	**0**
14	5	16800000	**14400000**	**14400000**	376.944	**255.084**	337.281	**0**	**0**	**0**
14	7	**208000000**	234000000	215000000	2362.521	**2197.001**	2275.122	**8**	9	**8**
14	10	260000000	259000000	**236000000**	3452.525	**3085.414**	3310.143	16	**11**	14
16	2	464000	560000	**365000**	25.5	**18.455**	20.377	**0**	**0**	**0**
16	3	10900000	10900000	**7580000**	435.885	**279.153**	317.886	**0**	**0**	**0**
16	4	81400000	**73200000**	74600000	2695.172	**1872.869**	2437.614	9	**4**	6
18	2	3680000	4570000	**2730000**	265.789	**178.755**	203.287	**0**	**0**	**0**
18	3	45400000	67100000	**44600000**	2864.808	**2692.193**	2823.943	13	**9**	12
18	4	132000000	**121000000**	130000000	3531.263	**3492.868**	3507.656	**19**	**19**	**19**
20	2	14700000	22700000	**12300000**	1417.233	**1157.732**	1159.092	**1**	**1**	**1**
20	3	64900000	93100000	**62300000**	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
20	4	140000000	149000000	**100000000**	**3600.001**	**3600.001**	**3600.001**	**20**	**20**	**20**
Average		38532676.30	41593983.70	**35592996.30**	940.27	**856.47**	899.90	3.93	**3.44**	3.70

The RPD was calculated for all databases separately, and the results are shown in Table 5.

Table 5. RPD of the variations of the LB for all databases

Database	Ave. Node Count			Ave. CPU Time (ms)			Number of Unsolved		
	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3	LB_1	LB_2	LB_3
Database 1	**0.00**	0.06	**0.00**	0.07	**0.00**	0.06	0.04	**0.00**	0.04
Database 2	0.12	0.14	**0.00**	0.11	**0.00**	0.04	0.14	**0.00**	0.07
Database 3	0.10	0.13	**0.00**	0.12	**0.00**	0.06	0.12	**0.00**	0.02
Database 4	0.08	0.17	**0.00**	0.10	**0.00**	0.05	0.14	**0.00**	0.08
Average	0.08	0.13	**0.00**	0.10	**0.00**	0.05	0.11	**0.00**	0.05

From Tables 1, 2, 3, and 4 it was possible to notice that the bigger the setup times, the smallest is the number of nodes for all variations of the LB. Thus, it can be noted that this factor is not significant for the comparisons. From Table 5 it was possible to observe that for all different databases the lower bound LB_3 was the one that most reduced the number of nodes. On the other hand, LB_2 solved more problems in less computational time. The results of LB_1 proved to be inefficient for all databases. As the most important measure for the B&B algorithm is computational time, it can be considered that the search of $Setup_k(j)$ is impracticable for the problem studied in this paper.

5 Conclusion

This paper considers a blocking permutation flow shop scheduling problem with the total flow time criterion, which is known to be NP-hard for $m \geq 2$. A machine based lower bound that exploits the occurrence of blocking and idle time (LB) is proposed and applied to the branch-and-bound algorithm. Four setup time databases were generated, each with different values range. The tests show that this range value did not affect the LB performance.

As no other lower bound was found in the literature, three different ways of applying the proposed LB were studied and compared. LB_1 got the worst computational time and was the variation that solved less problems within 3600 seconds, also got the second

worst number of nodes. So, it can be concluded that including both $S_{i[1]k}$ and $S_{[1]jk}$ in the search is important for the LB.
Overall LB_3 got the smallest number of nodes and LB_2 got the smallest computational time and number of unsolved problems. This can mean that including $Setup_k(j)$ in the search is not interesting for the LB.
For future works, the development of a dominance rule for pruning a higher number of nodes and the use of efficient heuristics as initial upper bounds are suggested. These suggestions aim at improving the algorithm, while applied along with LB_2. Furthermore, other exploration rules may be tested, such as the best bound rule, or a hybrid technique. Considering the efficiency of the proposed LB, another suggestion is to apply the rules used for incorporating the blocking constraints in this LB into a general case with a limited buffer greater than or equal to zero.

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Suporte a tomada de decisão em processos em saúde usando BPMN e DMN

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Resumo. A tomada de decisão na área da saúde é uma atividade complexa. Assim, diversas ferramentas têm sido desenvolvidas a fim de dar suporte ao usuário durante este processo. Uma destas ferramentas é a abordagem de questionário, utilizada em modelos de processo desenvolvidos em BPMN (*Business Process Model and Notation*). Além disso, a modelagem de processos focada nas decisões, como o DMN (*Decision Model and Notation*), está ganhando destaque, tanto na literatura quanto nos ambientes de negócios. Neste contexto, esta pesquisa tem como objetivo analisar o suporte à tomada de decisão fornecido pela abordagem de questionário em modelos de processo desenvolvidos em BPMN e DMN. Assim, essas linguagens foram utilizadas para a modelagem de um dos tratamentos disponíveis para pacientes diagnosticados com acidente vascular cerebral (AVC). Foi realizado um estudo da literatura a fim de investigar como o BPMN e o DMN vêm sendo empregados no apoio à decisão para processos na área da saúde. Também é apresentada a aplicação do BPMN e DMN junto à técnica de modelo de questionário no processo para tratamento do AVC. Para finalizar, a análise comparativa das duas técnicas é apresentada, mostrando que, em DMN, o processo apresenta um ganho considerável na simplificação visual do processo quando o foco é a observação das decisões. Também, quando aplicado junto ao modelo de questionário, é evidente que tal técnica torna muito mais fácil o processo de implementação de ferramentas para apoio a decisão durante o caminho clínico.

Palavras-chave: Configuração de Processo; Decisão; BPMN; DMN.

1 Introdução

A tomada de decisão na área da saúde é uma tarefa complexa, pois envolve diversos fatores, tais como diretrizes clínicas, sintomas dos pacientes, sistema de saúde, recursos disponíveis, entre outros [1]. Além disso, decisões nesta área envolvem múltiplos objetivos que muitas vezes são conflitantes [2]. Desta forma, processos na área da saúde devem ser flexíveis, ou seja, devem ser capazes de lidar tanto com mudanças esperadas como não esperadas, que afetam apenas algumas partes do modelo [3], [4]. Portanto, a tomada de decisão é representada nos modelos de processo de negócios. Porém, está

representação pode mudar conforme a linguagem utilizada. Diversas linguagens e métodos foram desenvolvidos para a modelagem de processos de negócios, tais como o BPMN (*Business Process Modelling Notation*) e o DMN (*Domain and Model Notation*). O BPMN têm sido amplamente utilizados para modelagem de processos. Porém, estes modelos podem ser complexos e de difícil compreensão. Além disso, o BPMN não considera as decisões lógicas do modelo de processo. Assim, o DMN surgiu a fim de preencher esta lacuna, possuindo, em seu escopo, uma notação mais simples. O DMN é visualmente um modelo simplificado do seu equivalente em BPMN, contendo as atividades agrupadas por decisões. E, internamente, dentro das fases que geram decisões, tabelas que possuem os critérios a serem avaliados. Sendo assim, capaz de apresentar, de forma resumida, a estrutura lógica do processo e cada critério avaliado em seu respectivo momento [5]–[8]

Nestas linguagens, partes do processo são caracterizadas por pontos em que são apresentadas duas (ou mais) opções ao usuário e, em que ele deve selecionar uma delas de acordo com os requisitos estabelecidos. Estes pontos são chamados de pontos de decisão ou pontos de variação [9]–[11]. Assim, fornecer suporte ao usuário durante este processo é fundamental para alcançar os resultados esperados. Ao levar isso em consideração, algumas abordagens foram desenvolvidas a fim de auxiliar o usuário durante esta tarefa. Uma destas abordagens, chamada abordagem do modelo de questionário, foi desenvolvida por [12] e, nela, cada ponto de decisão se refere à uma questão e as alternativas existentes para cada questão se referem a um caminho a ser selecionado no modelo do processo.

Neste contexto, esta pesquisa tem como objetivo aplicar o modelo de questionário tanto com o BPMN como o DMN a fim de analisar como a decisão é abordada em ambas as linguagens, bem como compreender os benefícios resultantes e os gaps existentes. Assim, este artigo é organizado da seguinte forma: na Seção 2 são apresentados os trabalhos correlatos, a Seção 3 apresenta a linguagem BPMN em conjunto com a abordagem de questionário aplicada ao tratamento de AVC. Na Seção seguinte é apresentada a modelagem do processo referente ao tratamento de AVC em DMN aplicando a abordagem de questionário. A Seção 5 apresenta a discussão.

2 Trabalho correlatos

Devido à complexidade existente na área da saúde, diferentes métodos foram utilizados a fim de dar suporte ao usuário durante a tomada de decisão. [13] aplicaram a análise de decisão por multicritérios (MCDA) a fim de priorizar os critérios relevantes na tomada de decisão. Já [14] desenvolve a automatização de um caminho clínico, e o integra aos controladores hospitalares do paciente, explicitando a importância do desenvolvimento de processos de decisão e auxílio à decisão para o processo hospitalar.

Em relação ao BPMN, [15] modela um processo hospitalar com o intuito de auxiliar a gestão e proporcionar uma melhor visualização dos processos a fim de promover melhorias. [16] propõem um framework de suporte à decisão na área da saúde. Em seu framework o processo referente ao tratamento de AVC isquêmico é modelado em

BPMN. Os autores utilizam em conjunto a abordagem de modelo de questionário e ontologias a fim de dar suporte ao usuário durante a tomada de decisão.

Por sua vez, apesar de sua ampla aplicação, o uso do DMN na área da saúde é escasso. De forma que, sua aplicação, tem focado na transformação de processos configurados em BPMN para DMN, extraindo seu modelo lógico e apontando boas práticas para tal transformação. Como o DMN é uma abordagem mais recente, e apresenta uma abordagem mais focada ao processo decisório é fundamental compreender as melhores formas de realizar essa conversão [17]–[19]. [20] desenvolvem uma ferramenta de visualização para gestão de infecções baseada tanto em BPMN quanto DMN. [21] também aborda o uso de DMN, junto a um software, como base para tomadas de decisões flexíveis, tornando os processos baseados em dados e customizáveis. Assim, esta pesquisa visa analisar a aplicação da abordagem de questionário tanto com o BPMN como o DMN, a fim de compreender os benefícios resultantes e os gaps existentes. A próxima seção apresenta abordagem de questionário aplicado a um processo desenvolvido em BPMN e DMN.

3 Decisão com Business Process Model Notation (BPMN)

É notável o uso do BPMN para processos, sendo, inclusive, uma das linguagens de modelagem mais populares devido a sua versatilidade. De acordo com [6], o BPMN, entre todas as linguagens de modelagem de processos disponíveis foi amplamente aceito na indústria e na academia. Desta forma, o BPMN pode ser definido como uma ferramenta, na qual processos são definidos como uma sequência de atividades, pontos de decisão (caracterizados por gateways do tipo OR) e de paralelização (caracterizados por gateways do tipo AND), reguladas por mecanismos, como avaliações (decisões) ou eventos (situações que podem ocorrer em determinado momento) que direcionam o processo para determinada rota a fim de atingir um objetivo específico [22].

O BPMN é uma linguagem composta por diversos elementos, tais como, atividades, eventos, pools, lanes, gateways, artefatos e conectores. Porém, esta é uma linguagem simples e de fácil entendimento, capaz de mostrar o fluxo de execução das atividades, bem como proporcionar suporte a informação [23]. A **Fig. 1** apresenta um exemplo de um fragmento do processo desenvolvido em BPMN aplicado ao processo de infusão de rt-PA em pacientes com AVC isquêmico [24]. O AVC isquêmico acontece devido à formação de trombos em um dos vasos sanguíneos, interrompendo assim o fluxo sanguíneo em parte do cérebro [25]. Um dos tratamentos para o AVC isquêmico refere-se a infusão de trombolíticos (também chamado de infusão de rt-PA), os quais são capazes de dissolver os coágulos sanguíneos e podem ser utilizados até 4 horas e 30 minutos após o início dos sintomas.

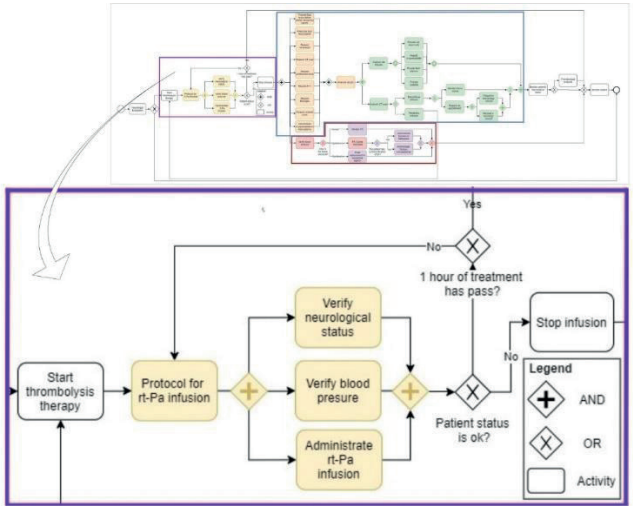

Fig. 1. Processo de infusão de rt-PA em BPMN. Adaptado de Detro *et al* (2019)

O processo apresentado na **Fig. 1.** é composto por diversas atividades (representados por retângulos), *gateways* (representados por losangos) do tipo OR (X) e AND (+). Em gateways do tipo OR, uma decisão deve ser tomada com base em alguma informação obtida ou resultado esperado. Tal decisão vai desencadear a execução de uma das sequências de atividades conectadas, ou seja, na seleção de um caminho, ou até mesmo no fim do processo. Por outro lado, *gateways* do tipo AND representam que as próximas atividades devem ser executadas em paralelo. Como exemplo, na figura, após a execução da atividade "*Protocol for rt-PA infusion*", encontra-se um *gateway* AND, mostrando que três atividades ("*Verify Neurological status*", "*Verify blood pressure*" e "*Administrate rt-PA infusion")* são executadas em paralelo. Após a execução destas atividades, encontra-se um gateway do tipo OR, no qual uma decisão deve ser feita levando ao fim da infusão ou a outro gateway do tipo OR (ou ponto de decisão).

Processos desenvolvidos em BPMN apresentam, muitas vezes, lógicas de decisões em seus diagramas, o que pode gerar modelos complexos e insustentáveis [17]. Em adição, processos em BPMN quando complexos não são escaláveis para múltiplas atividades devido a problemas de performance computacional [26]. Segundo [17], a metodologia BPMN não é feita para representar processos lógicos de decisão de forma detalhada, resultando em modelos "spaghetti", o qual representam uma situação em que muitos arcos se cruzam, tornando a interpretação complexa. Entretanto, para processos com menor quantidade de ramificações, o BPMN se apresenta mais simples para compreensão. Também, é fundamental destacar que, tal problema existe, muitas vezes, por que muitas pesquisas focam no aspecto de controle usando BPMN, e a análise do fluxo de dados acaba sendo menos estudada [8].

Conforme mencionado anteriormente, o BPMN em conjunto com a abordagem de questionário pode dar suporte à tomada de decisão. A abordagem do modelo de questionário quando aplicada ao modelo de processo desenvolvido em BPMN, permite uma maior compreensão a respeito da lógica do processo, bem como um maior controle no

que diz respeito a ordem em que as opções são apresentadas aos usuários durante a configuração do processo. Para tal, a abordagem de modelo de questionário pode ser aplicada para auxiliar o usuário final. Além disso, esta abordagem limita as opções nos pontos de decisão, impedindo escolhas inconsistentes [12].

Dessa forma, [27] ressaltam que um modelo de questionário compreende um conjunto de fatos correspondentes a um conjunto de perguntas que são expressas em linguagem natural, de modo que, cada um desses fatos corresponde a uma variável booleana que representa uma característica particular. Por sua vez, [12] também apresenta o desenvolvimento de um modelo de questionário que considera a variabilidade do processo. Tal variabilidade de informações deve ser organizada de modo a possibilitar uma estrutura de escolhas. Essa estrutura determina as ações que devem ser seguidas no processo. Então, o sistema associa que cada questão se refere a um conjunto de fatos que podem ser verdadeiros ou falsos. Tais fatos se traduzem na variabilidade do sistema (valores de parâmetros). Assim, conforme o questionário é respondido, os valores são associados a fatos. E por sua vez, define-se automaticamente quais serão as próximas questões, de modo a não exibir questões irrelevantes. A **Fig. 2** mostra um fragmento referente a aplicação da abordagem do modelo de questionário no modelo de processo desenvolvido em BPMN referente ao tratamento de infusão de rt-PA para pacientes diagnosticados com AVC isquêmico.

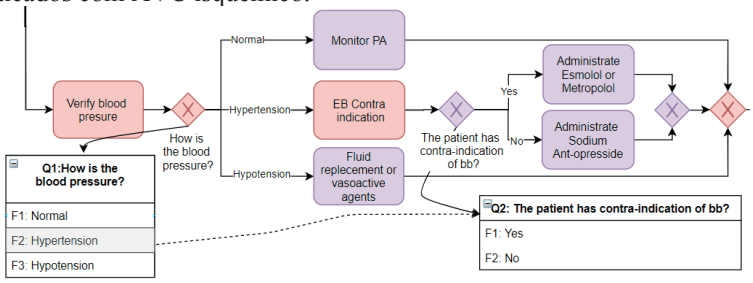

Fig. 2. Monitoramento do paciente em BPMN com modelo de questionário

Este fragmento do processo apresenta dois pontos de decisão (representados por gateways do tipo OR). O primeiro ponto de decisão, referente à questão Q1 "*How is the blood pressure*?", possui três opções possíveis. Caso o usuário selecione as opções "F1:Normal" ou "F3:Hypotension", as atividades executadas serão '*Monitor Pa'* ou '*Fluid replacement'*, respectivamente. Neste caso, nenhuma nova pergunta é habilitada. Porém, se a opção selecionada for "F2:Hypertension", então a pergunta Q2 "*The patient has contra-indication of bb (beta blockers*)?" é habilitada a fim de direcionar o tratamento correto. Por sua vez, em termos lógicos, se Q1 = F1 ou Q1 = F3 então o questionário é finalizado. Se Q1 = F2, então Q2 é habilitado e uma nova seleção deve ser feita pelo usuário. Assim, nota-se que a abordagem de questionário quando aplicada em modelos desenvolvidos em BPMN facilita a tomada de decisão e, conforme mencionado, esta abordagem permite que apenas as perguntas relevantes sejam apresentadas ao usuário. A próxima seção apresenta a aplicação da abordagem de questionário com modelos desenvolvidos em DMN.

4 Decisão com Domain Model and Notation (DMN)

Esta seção apresenta o desenvolvimento do modelo de processo em DMN referente ao tratamento de infusão de rt-PA em pacientes diagnosticados com AVC isquêmico, bem como a transcrição do modelo BPMN para DMN. Além disso, também é apresentado a aplicação da abordagem de questionário com um modelo de processo desenvolvido em DMN.

4.1 Funcionamento do DMN

Como visto na seção anterior, o BPMN não leva em consideração a lógica da informação dos processos [8]. [17] complementa que o modelo de decisão lógico está fora de escopo do BPMN. Assim, tabelas de decisão e outros conceitos de modelagem de decisões são um método razoável e compacto para descrever decisões em cenários com muitos parâmetros de entradas. [28] afirmam que o DMN pode ser usado também a fim de automatizar decisões e até mesmo automatizar análises para equipes de *business analytics*. Desse modo, o DMN é uma solução razoável para preencher o vazio da representação das decisões no aspecto de modelagem de processos [19].

O método DMN foi desenvolvido para modelar decisões e ser usado como complemento do BPMN para design de decisões. [29] apresenta o DMN como uma ferramenta cujo principal objetivo da sua notação é mostrar uma visão lógica e orientada por objetos. Entretanto, tal como aponta [30], a modelagem de decisões é desafiadora e definir como a modelagem será feita é um fator crucial para o resultado. [19] explica que o processo para desenvolvimento do DMN possui dois níveis que devem ser usados em conjunto, conforme mostra a **Fig. 3**.

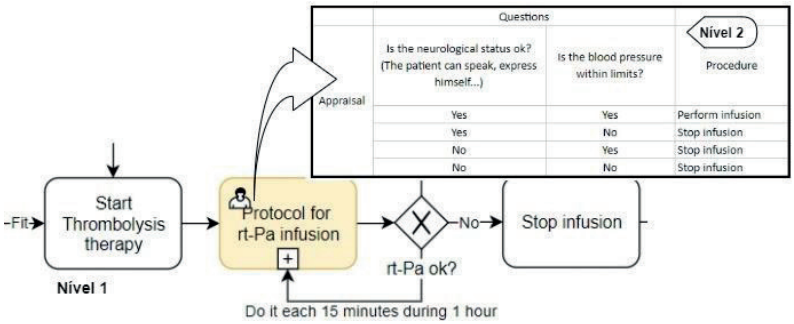

Fig. 3. Processo de infusão de rt-PA em DMN com seus dois níveis.

O primeiro nível é o de solicitação da decisão que apresenta as decisões no modelo, conforme apresentado na **Fig. 3**, a qual apresenta o fragmento referente ao processo para a infusão de rt-PA para o tratamento de pacientes com AVC. O nível 1 deste processo em DMN, assim como no BPMN apresenta as atividades em retângulos. Porém, de forma geral, as atividades no DMN são concentradas em uma só. Assim, por mais que no BPMN as atividades também possam ser concentradas em subprocessos, no DMN elas se transformam, visualmente, em tabelas e não em uma segunda camada do

diagrama. Assim, no DMN, a atividade "Protocol for rt-PA infusion" concentra as micro atividades de "Verify Neurological Status", "Verify Pressure", "Administrate rt-Pa infusion" junto a ela. Estas três atividades são executadas em paralelo.

Já no segundo nível do modelo lógico, são apresentadas as maneiras de especificar a lógica de decisão subjacente. E, por sua vez, podem ser exibidos para o usuário final em forma de modelo de questionário para auxiliar na decisão. A tabela apresenta as opções para o primeiro ponto de decisão considerando todas as possibilidades. Assim, as micro atividades podem ser condensadas em uma tabela de decisão. Deixando, no DMN, as possibilidades mais claras que no BPMN, mesmo com o questionário aplicado. Para a elaboração do DMN, geralmente realizado por transição de um BPMN, é necessário explicitar, tal como afirma [18], que não é claro qual informação/processo carrega valor de decisão e como a variabilidade de processos deve ser diferenciada quando externalizada para um modelo de decisão.

4.2 Transcrição do processo em BPMN para DMN

Na aplicação do DMN, todo o processo, representado em BPMN por meio de diagramas e gateways de decisão, deve estar presente no DMN, devidamente traduzido em sua própria linguagem. Entretanto, deve ser dado destaque aos pontos de decisão. Referente ao primeiro nível, que é constituído primeiro, é fundamental analisar a estrutura em BPMN e identificar: 1. Quais pontos de decisão podem ser simplificados/unidos; 2. Quais pontos de decisão devem ser mantidos; 3. Quais pontos de decisão devem ser reorganizados; 4. Quais critérios são avaliados em cada momento de decisão; 5. Quais critérios são avaliados ao mesmo tempo; 6. Quais critérios são dependentes entre si;

Então, com o mapeamento realizado e feito a análise da estrutura em BPMN, deve-se criar o diagrama, o qual é apresentado na **Fig. 4**. O diagrama, anteriormente em BPMN, com 38 pontos de atividade e 13 pontos de decisão e/ou paralelização; é composto por apenas 10 blocos de processo e 5 pontos de decisão. De modo que as transformações para adequação do modelo, em termos do primeiro nível, são destacadas nos próximos parágrafos.

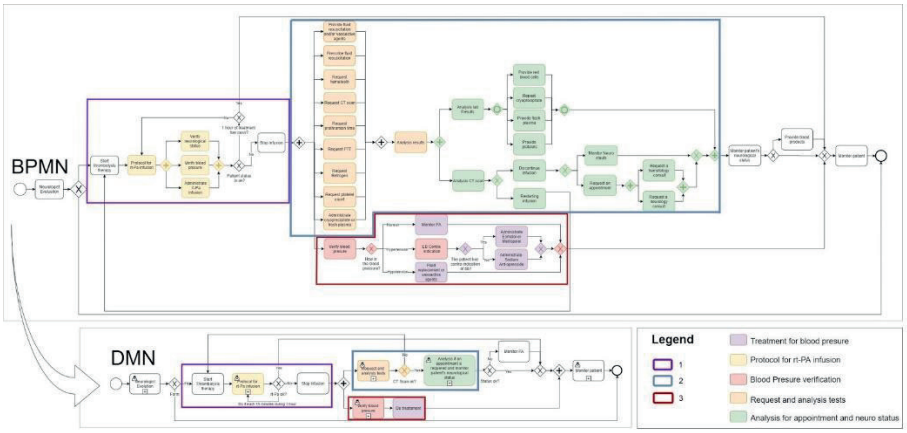

Fig. 4. Resumo das transcrições do Processo de AVC em BPMN para DMN.

Primeiramente, tem-se o subprocesso de infusão de rt-PA que inicia com a atividade "*Protocol rt-Pa infusion*". Após sua execução, as atividades "*Verify neurological* status", "*Verify blood pressure*", "*Administrate rt-Pa infusion*" são realizadas em paralelo. Na sequência existe um gateway do tipo OR(X). Neste gateway, deve-se verificar o resultado dos três processos realizados no paciente e identificar se o mesmo é capaz de continuar o processo. Se o paciente apresentar sintomas de hemorragia ou pressão alta, a infusão deve ser encerrada ("*Stop infusion*"). Caso contrário, o segundo *gateway* OR é verificado. Neste gateway, deve-se verificar o tempo de infusão. Se o tempo for menor que o prescrito pelo neurologista, a infusão e a verificação do status do paciente continuam. Caso contrário, a infusão é finalizada. Este fragmento do processo contém 5 blocos de atividades, dois símbolos de AND e dois símbolos de OR e, podem ser simplificados para duas atividades: "*Protocol for rt-Pa infusion*" e "*Stop Infusion*". Neste caso, as atividades de verificação do status do paciente são simplificadas na atividade "*Protocol for rt-Pa infusion*" e se referem a apenas 1 bloco de OR;

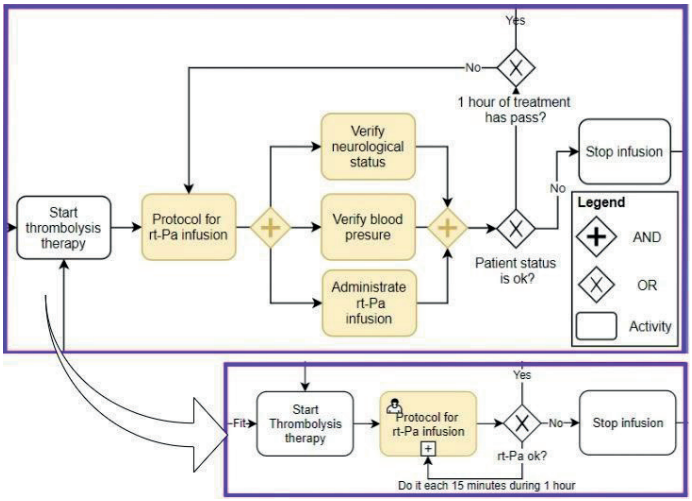

Fig. 5. Transcrição do processo de infusão de rt-PA

Já, se a atividade "*Stop infusion*" for executada, então, serão executadas atividades referentes a requisição de exames, bem como as análises destes exames. De modo que, no BPMN, o processo é composto por nove blocos de requisições médicas, seguido de um bloco de análise de resultados que, por meio do gateway AND, divide em mais cinco blocos as análises dos resultados do laboratório e outros sete blocos as análises da tomografia computadorizada e, em caso de necessidade, o agendamento de consulta com médico (neurologista ou hematologista). Totalizando vinte e dois blocos de atividades, seis blocos de AND, dois blocos de EVENT e três blocos de decisão. Estes blocos podem ser reduzidos no DMN para quatro blocos de atividades, três blocos de decisão e um bloco AND. De modo que os nove blocos de requisições médicas, os blocos de análises em laboratório e os blocos de análises da tomografia computadorizada foram agregados em "*Request and analysis tests*", de forma que, como output, a decisão sobre a necessidade de continuar a infusão e solicitar consulta gera um bloco OR (de

decisão) e define a necessidade de realizar uma consulta ou então de refazer o processo de infusão de rt-Pa.

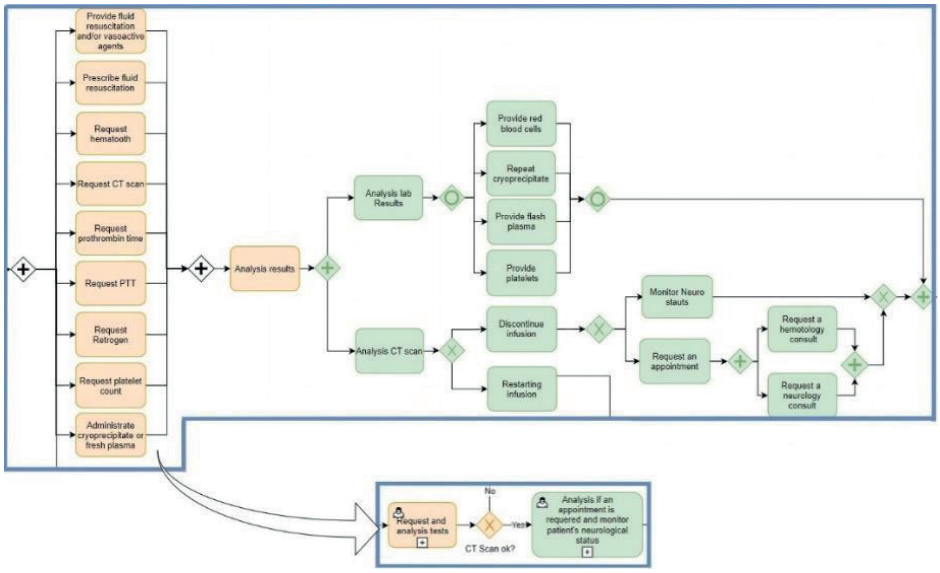

Fig. 6. Transcrição do processo de avaliação

Por sua vez, o subprocesso de monitoramento de infusão em BPMN é composto por seis blocos de atividades e quatro blocos OR de decisão, que podem ser agregados em 2 blocos de atividades. Um "*Verify blood pressure*" e na sequência as atividades de "*Monitor PA*", "*EB Contra indication*" (que gera "*Administrate Esmolol or Metropolol*" e "*Administrate Sodium ant-opresside*"), e "*Fluid replacement or vasoactive agents*" podem ser agregadas em "*Do treatment*";

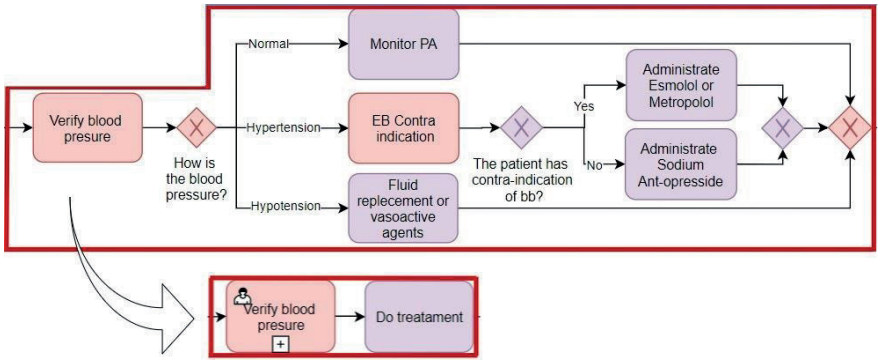

Fig. 7. Transcrição do processo de monitoramento de infusão

Também, os processos de "*Monitor PA*", "*Monitor Patient*" e "*Neurologist Evolution*" são mantidos. E por fim, é fundamental citar que no processo de "*Neurologist*

Evolution" o formulário referente a qualificação do paciente para o tratamento foi adicionado como input para a decisão do procedimento.

Após a criação do diagrama, o próximo passo é a sua validação. Se validado, é possível então, partir para o segundo nível que se refere a composição das tabelas de decisão. Tabelas essas, que são compostas por diversas perguntas (*inputs)* que retornam uma resposta (*output)*. De modo que, tal resposta define o caminho que o DMN vai seguir no DRD. Nesta segunda etapa, com o mapeamento feito anteriormente e com o diagrama construído é possível desenvolver as tabelas que contêm o detalhamento dos *inputs* e *outputs* para cada ponto de decisão. De modo que, como padrão, para *n* colunas, cada uma dessas colunas (de 1 até *n*-1) é referente a uma pergunta (*input)* e a última (*n*) é referente a resposta (*output)*. Assim, cada linha na tabela é referente a uma combinação de perguntas e sua respectiva resposta.

Além disso, é fundamental comentar que a complexidade dessas tabelas cresce de acordo com alguns fatores. O processo estudado possui tabelas com 20 colunas, com o número suficiente de linhas para todas as combinações possíveis. Entretanto, devido a seu tamanho, a sua complexidade aumenta. Tal complexidade, muitas vezes geradora de atrasos em termos computacionais, pode crescer nos seguintes casos: 1. Resposta da pergunta não ser binária ("Sim" ou "Não', 0 ou 1); 2. A resposta ter que ser segmentada em intervalos ("de 100 a 200" e de "250 a 300"), consumindo mais de uma coluna; 3. Número de *inputs;* 4. Número de opções de resposta para cada pergunta (muitas vezes as respostas podem ser uma lista).

Por sua vez, o modelo de questionário aplicado ao DMN também apresenta diversas simplificações e mudanças. Em sua aplicação, o modelo de questionário é aplicado nos pontos de atividade (retângulos) que possuem tabelas, como o "*Protocol for rt-Pa infusion*" citado em exemplos anteriores, enquanto que os questionários para o BPMN são resolvidos nos gateways OR(X). Portanto, como no DMN as decisões são coletadas nos retângulos de atividades, os pontos de decisão (XOR), neste trabalho, apenas representam diferentes caminhos que tal processo pode seguir. Além disso, a construção do diagrama do DMN tem como parte fundamental a construção das tabelas, conforme já citado anteriormente. Esse nível pode ser diretamente traduzido para o modelo de questionário, não necessitando a elaboração de lógicas para o questionário, conforme a Fig. 8.

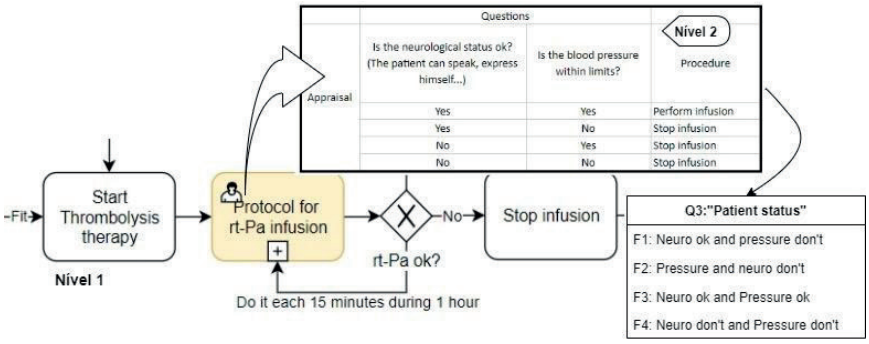

Fig. 8. Processo de infusão de rt-PA com questionário

5 Discussão

No estudo realizado, foi configurado um modelo em DMN suportado por uma abordagem de questionário, e então comparado com um modelo em BPMN também apoiado pela abordagem de questionário. Em tal comparação foi realizada a análise entre ambas as abordagens em relação a suas aplicabilidades e restrições. Para tal, foi usado o estudo de caso do processo do acidente vascular cerebral desenvolvido por [16]. De forma que, como notado na literatura, poucos autores tratam do uso de DMN na área da saúde devido tal técnica ser recente. Muitos dos trabalhos a respeito do DMN focam na transformação do processo desenvolvido em BPMN para DMN ou na integração de ambos modelos. Por outro lado, a abordagem de questionário, que pode ser utilizada em conjunto com o BPMN e o DMN, fornece suporte ao usuário na tomada de decisão. Além disso, devido às diferenças entre o BPMN e o DMN, a aplicação da abordagem de questionário pode mudar a forma como a decisão é tomada. E assim, esse trabalho é capaz de preencher o vazio encontrado referente a aplicação da técnica do DMN em processos na área de saúde e também da comparação entre processos de BPMN e DMN aplicados com modelos de questionário.

Então, ao comparar as técnicas, primeiramente verifica-se uma grande simplificação do diagrama do BPMN quando transformado para seu equivalente em DMN. Tal simplificação, para o processo aplicado, significou uma redução do fluxo, em BPMN, com 38 nós de processo e 13 pontos de decisão ou paralelização, para um estado, em DMN, de 10 nós de processo e 6 pontos de decisão no processo. Ou seja, uma diminuição de aproximadamente 73% na complexidade visual do processo e de aproximadamente 53% na redução do número de pontos de decisão que deveriam ser tomados. Também a simplificação, ao converter de BPMN para DMN, no desenvolvimento de modelos de questionários destinados a customização do processo é significativa. Pois, enquanto que em BPMN é necessário o desenvolvimento de lógica para cada possível resposta em cada nó de decisão para configuração do modelo. Em DMN, cada tabela se traduz diretamente em um questionário a ser respondido. Não necessitando assim de configurações lógicas mais elaboradas.

Por sua vez, a literatura apresenta um grande valor de resultados de busca em termos de desenvolvimento de suporte à decisão na área da saúde. Entretanto, poucos usam notações como BPMN e apenas uma pesquisa apresentou resultados sobre aplicação de DMN na saúde. [20] desenvolve uma ferramenta visual para suporte à decisão aplicada para a gestão de infecções baseado em BPMN e DMN. Sendo assim notável, tal como [17] expõem que o modelo lógico está fora de escopo do BPMN. E [31], complementa que o DMN não é um processo de modelagem padrão por si, é feito para modelagem da lógica do negócio. De modo que, torna-se evidente sua aplicação para processos orientados a decisão. Tal como [14] mostram, ao apresentar que o DMN, como técnica para o suporte de decisões, em seu uso clínico de sistemas de suporte a decisão está crescendo. De modo que, técnicas de suporte de decisão, levam a um aumento na adesão das diretrizes sobre prevenção de AVC. Porém, é fundamental ressaltar que o DMN ainda possui algumas contra partidas. [31] mostra que, como uma nova aplicação, o DMN requer um know-how novo sobre tal técnica. Afirma também que, tal técnica ainda não é tão conhecida como as demais e que sozinho não é capaz de definir um

processo. Sendo assim, como processos em DMN são transcritos de processos desenvolvidos em BPMN, [18] ressaltam que não é claro qual informação processual carrega valor de decisão, e qual dos vários tipos de processos ligados devem ser diferenciados quando externalizados em um DMN.

Logo, a pesquisa realizada encontrou suas restrições. Em primeiro lugar, observou-se processos com muitas variáveis de decisão ao mesmo tempo, tal como longos questionários, podem gerar tabelas muito complexas para o DMN. Afinal, é necessária uma linha na tabela para cada combinação de respostas, e cada combinação de respostas é um conjunto de variáveis de cada coluna. Portanto o tamanho de cada tabela é *n*x*m* (*n* sendo total de respostas possíveis e m sendo o número de perguntas) linhas por *m* colunas. Sendo fundamental ressaltar também que, em casos de combinações não lineares de resposta (sim, não), ainda maior pode ser o tamanho dessas tabelas. Além disso, é notável que o DMN esconde subatividades, que podem ser cruciais em análises de maior granulação. Portanto, é fundamental explicitar que, muitas vezes é necessário trabalhar com o BPMN também lado a lado.

Também, é fundamental destacar que tal trabalho ainda possui muito a ser desenvolvido. Em primeiro lugar, é natural a possibilidade de uma análise multicritérios junto ao DMN aplicado a tomada de decisão, de modo que, tendo o questionário, existe a possibilidade de dar sugestões ao usuário para que ele selecione a melhor opção de acordo com um resultado específico. Assim, outro caminho possível é o uso da técnica AHP (*Analytic Hierarchy Process*) junto com o modelo de questionário e com DMN como forma de dar dicas e apoio durante o processo decisório, porém aplicados a outros processos. Também, existe a necessidade de pré análise para otimização das perguntas ou fatores decisivos no processo, avaliando assim suas reais relevâncias e impactos. Em adição, é relevante o desenvolvimento da aplicação desse trabalho em outros processos e comparação entre eles, afinal é fundamental compreender a real aplicabilidade dessa abordagem em outros cenários.

6 Conclusão

Neste trabalho foi proposto um modelo de processos focado em decisão aplicado ao processo hospitalar do Acidente Vascular Cerebral (AVC), desenvolvido em DMN, em conjunto com um modelo de questionário a fim de facilitar a usabilidade para o usuário final. Assim, a partir da compreensão e análise do modelo do processo do AVC em BPMN e do estudo da funcionalidade do DMN foi possível perceber que nesse processo, quando orientado com foco nas decisões, pode ser melhor compreendido se desenvolvido em DMN. Afinal, tal técnica simplifica a complexidade de visualização dos modelos. Também, quando aplicado junto ao modelo de questionário evidencia-se que a sua implementação se torna muito mais fácil. Pois, dessa forma, não é necessário a configuração de regras lógicas de (se-então) para os questionários. E assim, o DMN se mostra capaz de ser mais eficiente ao ser implementado.

Porém, os modelos desenvolvidos não foram comparados com outros processos a fim de avaliar se o ganho do desenvolvimento em DMN é realmente significativo para todos os casos. Ou então, para compreender em que casos que tal implementação é

relevante. Também, sistemas não foram desenvolvidos para implementar, testar e comparar ambas abordagens com outros processos. Logo, tais observações levantadas na pesquisa precisam ser validadas em pesquisas futuras.

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Mathematical Modeling of ARGET Copolymerization of Styrene and Acrylonitrile. I: Experimental Validation

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Abstract. A precise control on the molecular structure is required to enhance the development of innovative polymers. Reversible Deactivation Radical Polymerization (RDRP) techniques allow to synthesize advanced molecular structures without stringent purity conditions, which improves their potential for industrial manufacturing. In particular, the RDRP variant Activators ReGenerated by Electron Transfer – Atom Transfer Radical Polymerization (ARGET-ATRP) presents additional advantages, such as requiring very low concentration of transition metal catalyst. This reduces significantly the need of post reaction removal of residual catalyst and consequently the polymer purification cost. In addition, ARGET-ATRP tolerates a limited amount of air in the reaction environment.

In order to enhance the cost-performance ratio it is important to optimize the production process. Mathematical modeling is a powerful tool, extensively used to improve production time and process control. Part I and Part II of this work present a very detailed mathematical model of ARGET-ATRP copolymerization of styrene and acrylonitrile (SAN). Part I is devoted to the estimation of the kinetic parameters of the model. A good agreement between model and experimental data is achieved. Part II describes in detail the modeling of the bivariate molecular weight distribution-copolymer composition distribution of the copolymer, as well as the overall molecular weight distribution and copolymer composition distribution, using parallel computing and an efficient programming language.

Keywords: Copolymerization, ARGET-ATRP, Parameter Estimation, SAN.

1 Introduction

Reversible Deactivation Radical Polymerization (RDRP) has been one of the most important developments of polymer chemistry in the last decades. This family polymerization techniques make possible the synthesis of materials with prespecified molecular structures with unique physicochemical properties.

RDRP relies on adding a control reagent that reversibly deactivates radicals. When the radical chain is in its dormant state it cannot participate in any reaction, which minimizes radical termination. In this way, the lifetime of a growing polymer chain is extended from approximately a second to hours, allowing the manipulation of its molecular structure by implementing appropriate operating policies. Moreover, RDRP combines the high degree of control on the polymer properties with the ease of large-scale implementation of a free radical polymerization. However, presumably due to the need of removing control agent residues or by-products and to the higher cost resulting from the use of expensive control reagents, the number of commercial products produced with this technology is a lot less than initially expected [1].

New RDRP mechanisms have been developed that overcome most of its drawbacks. Activators ReGenerated by Electron Transfer – Atom Transfer Radical Polymerization (ARGET-ATRP) is one of the most promising techniques. Conventional ATRP relies on adding a transition metal salt (usually CuBr or CuCl) that traps the radical and when it oxidizes acts as activator. During termination processes, Cu^{II} species are irreversibly formed and, therefore, more Cu^{I} salt is needed to continue the polymerization. In ARGET-ATRP, the Cu^{I} species are (re)generated in the reaction medium from the oxidized Cu^{II} salt using a reducing agent. In this way, only the oxidized and more stable Cu^{II} salt has to be handled, facilitating the synthesis process. Besides, the amount of Cu salt that remains as residue is drastically decreased, sometimes eliminating the need of purification procedures.

The benefits of the better performance showed by the materials obtained by RDRP in general and by ARGET-ATRP in particular may not be enough to justify the higher production costs. Moreover, many of these costs are due to the purification processes required to eliminate the control agent residues and non-reacted monomers. These process flaws can be reduced with an efficient and accurate model [2]. Modeling is a powerful tool, extensively used to improve production times and process control. Programmed feeding policies have allowed to synthetized targeted structures [3] and to improve reaction conversion [4]. In this context, a reliable set of parameters is crucial to carry out successful simulations.

Styrene-acrylonitrile (SAN) copolymer is a thermoplastic often used as structural material thanks to its processability, solvent resistance and thermal stability [5]. Moreover, these superior properties make it a good potential candidate for use in polymer blends. However, poor compatibility has been encountered in many cases due to polymers immiscibility [6]. In this regard, block or gradient copolymers have shown a promising performance since they could improve the interfacial adhesion of different phases [7]. In most cases, these types of copolymers can only be obtained by means of RDRP techniques. The course of polymerization strongly depends on the initial composition and the feeding policy [4, 8], so a mathematical model is a very important tool for the operation of the process. Few works have dealt with the modeling of ARGET-ATRP processes and most of them have relied on kinetic parameters found in the literature [9-14]. In particular, modeling studies of the RDRP of SAN polymers are scarce.

Part I and Part II of this work present a very detailed model of the ARGET-ATRP of SAN. Part II focuses on the efficient modeling of the bivariate molecular weight distribution (MWD)-copolymer composition distribution (CCD) of the copolymer, as

well as the overall molecular weight distribution and copolymer composition distributions, using parallel computing and a suitable programming language. Part I presents the estimation of the model kinetic parameters using experimental data taken from the literature [15].

2 Methods

2.1 Kinetic Mechanism.

The process under study in this work is the synthesis of poly(SAN) via ARGET-ATRP at 80ºC in solution of anisole using $CuCl_2$ as the transition metal catalyst and hexamethyl-tris(2-aminoethyl)amine (Me_6TREN) as ligand, ethyl 2-bromo iso-butyrate (EBriB) as radical initiator, and tin(II) 2-ethylhexanoate ($Sn(EH)_2$) as the reducing agent [15].

The mathematical model is based on the following kinetic mechanism:

Activation:

$$I - X + (X - Cu^I)L \xrightarrow{k_{act0}} I^* + (X_2 - Cu^{II})L \quad (1)$$

$$D^j_{n,m} + (X - Cu^I)L \xrightarrow{k_{actj}} R^j_{n,m} + (X_2 - Cu^{II})L \quad (2)$$

Deactivation:

$$I^* + (X_2 - Cu^{II})L \xrightarrow{k_{deact0}} I - X + (X - Cu^I)L \quad (3)$$

$$R^j_{n,m} + (X_2 - Cu^{II})L \xrightarrow{k_{deactj}} D^j_{n,m} + (X - Cu^I)L \quad (4)$$

Propagation:

$$I^* + M^1 \xrightarrow{k_{01}} R^1_{1,0} \quad (5)$$

$$I^* + M^2 \xrightarrow{k_{02}} R^2_{0,1} \quad (6)$$

$$R^j_{n,m} + M^1 \xrightarrow{k_{j1}} R^1_{n+1,m} \quad (7)$$

$$R^j_{n,m} + M^2 \xrightarrow{k_{j2}} R^2_{n,m+1} \quad (8)$$

Reduction:

$$(X_2 - Cu^{II})L + Sn^{II}(EH)_2 \xrightarrow{k_{r1}} (X - Cu^I)L + X - Sn^{III}(EH)_2 \quad (9)$$

$$(X_2 - Cu^{II})L + X - Sn^{III}(EH)_2 \xrightarrow{k_{r2}} (X - Cu^I)L + X_2 - Sn^{IV}(EH)_2 \quad (10)$$

Termination by Combination:

$$2I^* \xrightarrow{k_{tc00}} P_0 \quad (11)$$

$$I^* + R^j_{n,m} \xrightarrow{k_{tc0}} P_{n,m} \quad (12)$$

$$R^j_{n,m} + R^k_{d,\ t} \xrightarrow{k_{tcjk}} P_{n+d,m+t} \quad (13)$$

Chain Transfer to Monomer:

$$R_{n,m}^{j} + M^{1} \xrightarrow{k_{trm\,j1}} P_{n,m} + R_{1,0}^{1} \quad (14)$$

$$R_{n,m}^{j} + M^{2} \xrightarrow{k_{trm\,j2}} P_{n,m} + R_{0,1}^{2} \quad (15)$$

The polymerization starts with the reversible activation of the initiator EBriB (I-X) by the complexed copper catalyst in reduced state, (X-Cu^{I})L. In this reaction, the catalyst is oxidized ((X_2-Cu^{II})L) and an initiating radical (I*) is formed. Each I* will be the beginning of a polymer chain. In the propagation step the active radicals add monomer units (M^1=styrene, M^2=acrylonitrile) forming a longer radical chain ($R^j_{n,m}$) with *n* units of M^1 and *m* units of M^2 that ends in an M^j monomer unit. These propagating radicals will be periodically deactivated forming the dormant specie ($D^j_{n,m}$). Eventually, the growing chain could find another radical and undergo irreversible termination forming a "dead" polymer chain with *n* units of M^1 and *m* units of M^2 ($P_{n,m}$). The oxidized catalyst is reduced with the reducing agent ($Sn^{II}(EH)_2$) in a two-step process forming (X-$Sn^{III}(EH)_2$) and (X-$Sn^{IV}(EH)_2$), respectively.

The kinetic constant of activation and deactivation are different if the initial (I*) or a growing radical is reacting, i.e. if the reaction is the initiation activation or the core-equilibrium activation. Similarly, the kinetic constants of the propagation step are different if the reaction involves an initiating radical (I*) or a polymer radical ($R^j_{n,m}$). Chain transfer to polymer and termination by disproportionation were considered negligible [16, 17], as well as thermal initiation of styrene and terminal double bond propagation.

2.2 Mathematical Model.

The version of the mathematical model employed in Part I of this works uses the method of moments to compute average molecular properties, such as molecular weights and copolymer composition, and conversion [18]. Besides, it applies the 1D probability generating functions (pgf) technique to model the overall MWD of the copolymer. In this technique, the mass balances are transformed to the pgf domain. When doing so, the differential-algebraic equation system size is reduced leading to an easier resolution. After solving the pgf balance equations, the pgf are inverted to recover the MWD from the transformed domain using the IFG inversion method. Further details on this technique and its mathematical implementation may be found elsewhere [19, 20].

2.3 Estimation of Kinetic Parameters

The parameter estimation problem was formulated and solved in gPROMS ModelBuilder (Process Systems Enterprise, Ltd.) in a standard PC. gPROMS possess a state-of-the-art Parameter Estimation entity that maximize the probability that the model will predict the experimental data [21]. Multiple starting points were tested in order to minimize the chances of falling in a local optimum.

Experimental data of conversion, number-average molecular weight ($\overline{M_n}$), and dispersity ($Đ$) of six experiments taken from Pietrasik et al. [15] were used for the

parameter estimation. All the experiments were carried out with a molar ratio of S/AN of 60/40, which is the azeotropic composition for the mixture [15]. This implies that the copolymer is produced with this same composition, and that the monomer composition remains constant during the course of the reaction. Table 1 shows the experimental conditions of these experiments.

Table 1. Initial conditions of the experiments used in the parameter estimation problem. Reaction temperature: 80 °C. Solvent: anisole. Concentrations in mol/L [15].

Experiment	[S]	[AN]	[EBriB]	[$CuCl_2$]	[Me6Tren]	[$Sn(EH)_2$]
1	3.17	2.06	5.28×10^{-3}	5.28×10^{-5}	2.64×10^{-3}	2.64×10^{-3}
2	3.17	2.06	5.28×10^{-3}	1.59×10^{-4}	2.64×10^{-3}	2.64×10^{-3}
3	3.17	2.06	3.17×10^{-3}	1.59×10^{-4}	1.59×10^{-3}	1.59×10^{-3}
4	3.17	2.06	1.59×10^{-3}	2.62×10^{-4}	1.59×10^{-3}	1.59×10^{-3}
5	3.17	2.06	1.59×10^{-3}	1.59×10^{-4}	1.59×10^{-3}	1.59×10^{-3}
6	5.07	3.30	2.54×10^{-3}	7.62×10^{-5}	1.27×10^{-3}	1.27×10^{-3}

3 Results

The optimal set of kinetic parameters are shown in Table 2. There is a previous report about the rate constants of conventional ATRP of SAN [16], but, to the best of our knowledge, this is the first time that the kinetic constants of the activation/deactivation and reduction steps for the ARGET-ATRP of SAN have been obtained.

Table 2. Optimal values of the kinetic constants at 80 °C.
Units: L mol^{-1} min^{-1}

Reaction	Parameters	Optimal Value
Propagation	k_{01}	7.364×10^{3}
	k_{11}	7.364×10^{3}
	k_{02}	6.793×10^{6}
	k_{22}	3.397×10^{5}
	k_{12}	2.045×10^{4}
	k_{21}	4.354×10^{6}
Activation	k_{act0}	5.467×10^{3}
	k_{act1}	4.937×10^{3}
	k_{act2}	8.764×10^{4}
Deactivation	k_{deact0}	7.519×10^{5}
	k_{deact1}	6.278×10^{10}
	k_{deact2}	1.052×10^{15}
Reduction	k_{r1}	9.705

	k_{r2}	2.900×10^{4}
Termination by Combination	k_{tc11}	1.071×10^{8}
	k_{tc22}	9.006×10^{8}
	k_{tc12}	3.904×10^{7}
Chain Transfer to Monomer	k_{trm11}	1.987×10^{-2}
	k_{trm12}	5.977×10^{-1}
	k_{trm22}	1.351×10^{3}
	k_{trm21}	2.468×10^{3}

The mathematical model provides in general a good fit to experimental data, as shown in Figs. 1-4.

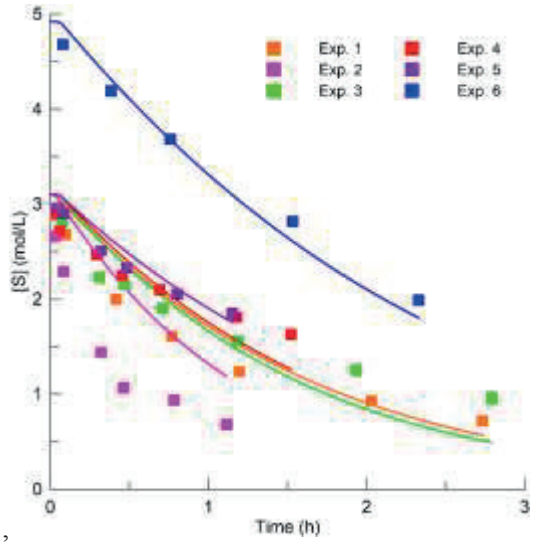

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Fig. 1. Comparison between experimental concentration of styrene (symbol) and model prediction (line).

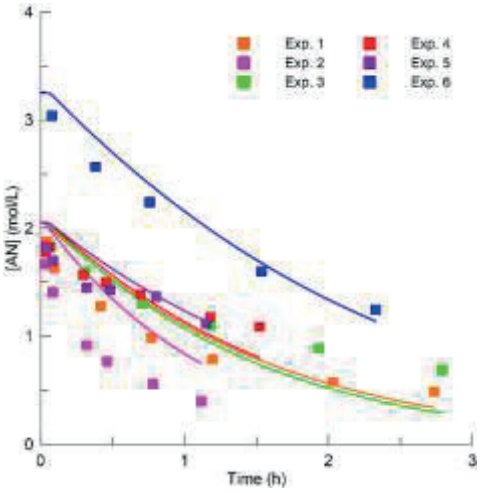

Fig. 2. Comparison between experimental concentration of acrylonitrile (symbol) and model prediction (line).

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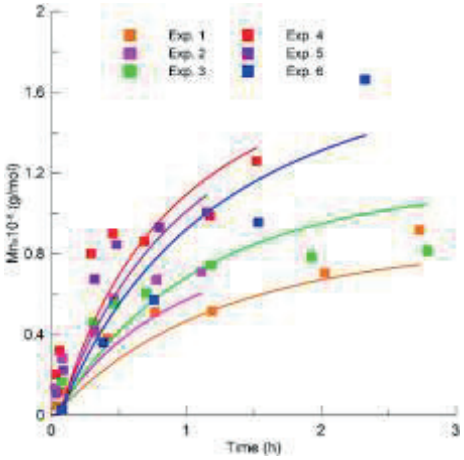

Fig. 3. Comparison between experimental number-average molecular weight (symbol) and model prediction (line).

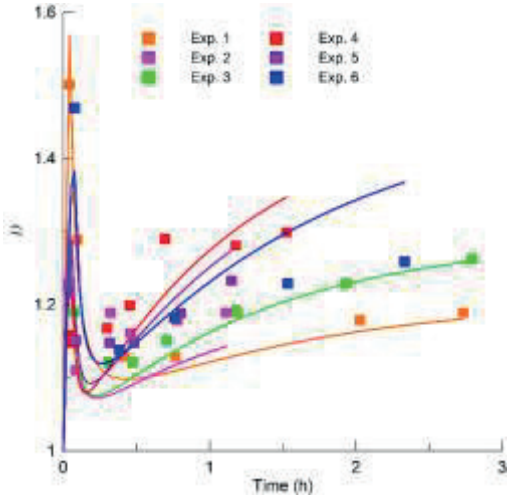

Fig. 4. Comparison between experimental dispersity (symbol) and model prediction (line).

The mathematical model may provide valuable insight on the process operation. For instance, Fig. 5 shows the average copolymer composition profile and the end-group functionality for Exp. 3 conditions. Note that the average copolymer composition remains spontaneously at the azeotropic point during the reaction, while the end-group functionality diminishes from 100 to 80 % with time. Fig. 6 presents the evolution in time of the MWD for this experiment. It shows that the MWD shifts to higher molecular weights while narrowing at the same time. However, a long low-molecular-weight tails grows at the same time, which is responsible for the increase in dispersity from 0.25 h to final time observed in Fig. 6.

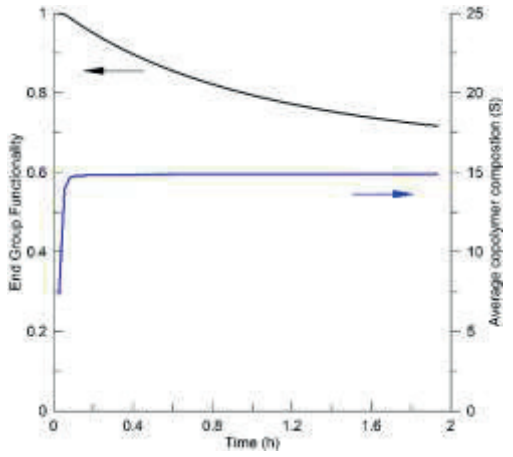

Fig. 5. Predicted average copolymer composition and end-group functionality profiles for Exp. 3 conditions.

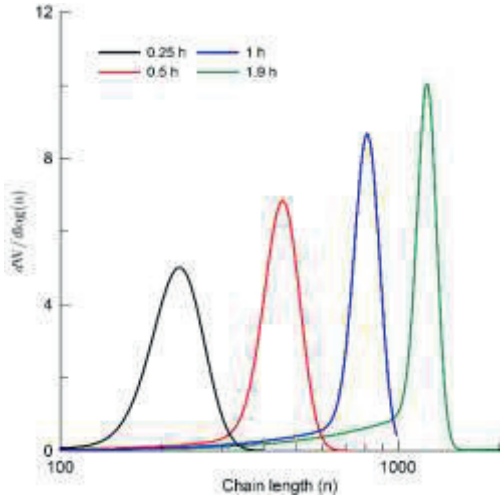

Fig. 6. Predicted MWD at different reaction time for Exp. 3 conditions.

4 Conclusion

The experimental data of MWD and average properties has been used to successfully estimate the rates constants of the ARGET-ATRP copolymerization of styrene and acrylonitrile. The set of kinetic parameters obtained allows to reproduce reasonably the experimental data. In addition, the model allowed to obtain prediction of properties that are considerably difficult to measure experimentally, such as copolymer composition and average end functionality.

The pgf technique is a powerful modeling tool of RDRP processes and can help to boost the development of innovative materials.

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Mathematical Modeling of ARGET Copolymerization of Styrene and Acrylonitrile. II: Efficient Calculation of Bivariate Distributions using Parallel Computing

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Abstract. The probability generating function (pgf) technique in combination with parallel computing is a very valuable tool for modeling bivariate distributions in polymerization systems. Models with this level of detail usually involve a very large system of stiff differential equations that demands efficient solution techniques. Part I of this work presented the parameter estimation of a mathematical model of the Activators ReGenerated by Electron Transfer – Atom Transfer Radical Polymerization (ARGET-ATRP) of styrene and acrylonitrile (SAN). A good agreement between model and experimental data was achieved. Part II focuses on the modeling of the bivariate molecular weight distribution (MWD)-copolymer composition distribution (CCD) of the copolymer, as well as the overall MWD and CCDs. Julia, an open-source language specifically designed for scientific computing, was used to implement the mathematical model. The parallelized implementation of the code in Julia allowed computing the bivariate distributions in relatively short times.

Keywords: Bivariate Distributions, Polymers, Modeling, Probability Generating Function, Parallel Computing, Open-Source Language, Julia.

1 Introduction

Activators ReGenerated by Electron Transfer – Atom Transfer Radical Polymerization (ARGET-ATRP) is one of the most versatile techniques to synthesize unique polymers with prespecified molecular structure. This technique has several advantages, such as the wide range of polymerizable monomers, the low cost and availability of reagents, and the possibility of achieving high molecular weight polymers. Moreover, unlike conventional ATRP, it uses the oxidized copper salt and a reducing agent as reagents. In this way, the control agent is formed in the reaction medium from the reduction of the Cu salt, which makes the handling of reagents much easier. Additionally, the reducing agent allows carrying out the polymerization in the presence of a few ppm of

oxygen that would otherwise contaminate the reaction [1]. Reversible Deactivation Radical Polymerization (RDRP) techniques, such as ARGET-ATRP, have the capability of synthesizing polymers with tailor-made properties that may have an outstanding performance in end-use applications. However, although several polymers produced via ARGET-ATRP are already being commercialized, its industrial development has not been as wide as initially expected [2]. Many times, the improvement in material performance does not justify the increase in production cost. It is clear that the polymerization process has to be optimized and that a highly detailed understanding of the relationship between molecular structure and operation conditions needs to be developed. Mathematical modeling has been widely used to improve production times and to optimize process operation. Moreover, if the model is fitted properly to the actual experimental behavior, it is expected to predict accurately the molecular structure with a high level of detail. Simulation can be used to predict properties that are hard to measure experimentally, optimize the reaction process, and design operating feeding policies to obtain targeted structures.

However, modeling polymer growth is challenging. A growing radical could theoretically add infinite monomers to the chain which will lead to infinite mass balances. It is possible to establish a maximum chain length and therefore reduce the number of equations to a reasonable yet large number. Even so, the size of the resulting differential-algebraic equations (DAE) system is large for most polymerization systems. Furthermore, since the kinetic rates of the reactions involved differ by several orders of magnitude and the concentration of radicals relative to that of the other polymeric species is always small, the stiffness of the DAE system is high and its resolution is really difficult.

The well-known method of moments is widely used to predict polymer average properties [3]. Any distribution has infinite moments which are quantitative parameters specifics to its shape and can uniquely determine it. Since only moments of order 0, 1, and 2 are required to obtain the average properties of interest in polymer science, the technique consists of transforming the infinite mass balances into the 3 balances for the needed moments.

On the other hand, obtaining the full distribution is very complex, since the infinite set of mass balances must be solved. A polymer sample may be characterized by different types of distributions. One of the most important ones is the molecular weight distribution (MWD). It affects both processing properties (melt temperature and flow properties in molten polymers) and mechanical properties (tensile strength, impact strength, etc.). Other important molecular properties are, for example, the copolymer composition distribution (CCD), the short-chain branch distribution (SCBD), and the long-chain branch distribution (LCBD). Having a tool that allows predicting these molecular properties based on the process conditions is highly desirable.

Several methods have been proposed for modeling the MWD. In these methods, the system of equations to be solved is, in general, quite large. The extension of these methods to the computation of multivariate distributions, that is, joint distributions of more than one molecular property, is even more complex. For this reason, a reduced number of approaches have been reported [4].

One of the main problems when solving these models is not only the complexity in their formulation but also the efficiency concerning computation times, data processing, CPU and RAM memory requirements. A computational technique that has the potential to speed up the execution of mathematical models is parallel computing. Most modern computers have CPUs with more than one core (typically 4-8). However, most of the applications reported in the literature for the calculation of multivariate distributions use serial calculation, which uses a single CPU core.

To solve a particular problem using parallel computing, the problem needs to be divided into independent sections, so that each section can be solved concurrently with the other ones. Not all the methods proposed for calculating multivariate distributions meet this condition. The probability generating function (pgf) technique [5, 6] is a very efficient method for modeling multivariate distributions and is particularly suitable for use with parallel computing.

The pgf method has been used previously for modeling univariate and multivariate polymer distributions [5, 7]. This technique is based on solving the transformed pgf equations of the infinite mass balances that describe a certain process and subsequently inverting the resulting pgf to recover the desired distribution.

Developing an algorithm designed for parallel computing generally requires more effort and time than one designed for serial computing. The use of the appropriate programming language is very important to facilitate this process.

In Part I of this work [8] a model of the ARGET-ATRP copolymerization of styrene and acrylonitrile (SAN) was implemented in gPROMS ModelBuilder (Process Systems Enterprise, Ltd.) to estimate the kinetic rate constants using experimental data from the literature [9]. This model calculated conversion, average molecular properties, and the overall, univariate MWD of the copolymer. Part II of this work presents an extension of this model that calculates the bivariate MWD-CCD, the overall MWD, and the overall CCD of the copolymer. The detailed mathematical model was programmed in Julia, which is an open-source programming language easy to use and that performs very fast calculations. The pgf is used to process the infinite mass balances of the system. The code developed in Julia allowed to predict the distributed copolymer properties in a very efficient manner.

2 Mathematical Model

The experimental set up considered in this work is the synthesis of poly(SAN) via ARGET-ATRP reported by Pietrasik et al. [9]. The polymerization is carried out at 80ºC in a solution of anisole using $CuCl_2$ as transition metal catalyst and hexamethyl-tris(2-aminoethyl)amine (Me_6TREN) as ligand, ethyl 2-bromo iso-butyrate (EBriB) as radical initiator, and tin(II) 2-ethyl hexanoate ($Sn(EH)_2$) as reducing agent.

The kinetic mechanism on which the mathematical model is based is detailed in Part I of this work [8]. The mathematical description of the polymerization system involves the following entities: styrene monomer (M^1), acrylonitrile monomer (M^2), polymeric radical chains with *n* units of M^1 and *m* units of M^2 with an M^j final unit ($R^j_{n,m}$), dormant species with *n* units of M^1 and *m* units of M^2 with an M^j final unit ($D^j_{n,m}$), and terminated

polymer chains with n units of M^1 and m units of M^2 ($P_{n,m}$), initiator EbriB (I-X), complexed copper catalyst in reduced state ($X\text{-}Cu^{I}$)L, complexed copper catalyst in the oxidized state (($X_2\text{-}Cu^{II}$)L), initiating radical (I*), reducing agent ($Sn^{II}(EH)_2$), oxidized reducing agent stage 1 ($X\text{-}Sn^{III}(EH)_2$) and oxidized reducing agent stage 2 ($X\text{-}Sn^{IV}(EH)_2$).

The mass balances of the polymeric species for a batch reactor derived from the kinetic mechanism are:

$$\frac{dV\left[R^j_{n,m}\right]}{dt}=\left(\begin{array}{l}-k_{deact\,j}\left[R^j_{n,m}\right]\left[\left(X_2-Cu^{II}\right)L\right]+k_{act\,j}\left[D^j_{n,m}\right]\left[\left(X-Cu^{I}\right)L\right]\\+\left\{\left(k_{trm\,jj}\,\lambda^j_{0,0}+k_{trm\,ij}\,\lambda^i_{0,0}\right)\left[M_j\right]\right\}\delta_{n,1\delta_{j,1}}\delta_{m,1\delta_{j,2}}\\+k_{ij}\left[M^j\right]\left[R^i_{n-1\delta_{j,1},m-1\delta_{j,2}}\right]+k_{jj}\left[M^j\right]\left[R^j_{n-1\delta_{j,1},m-1\delta_{j,2}}\right]\\+k_{0\,j}\left[I^*\right]\left[M^j\right]\delta_{n,1\delta_{j,1}}\delta_{m,1\delta_{j,2}}\\-\left\{\begin{array}{l}\left(k_{jj}+k_{trm\,jj}\right)\left[M^j\right]+\left(k_{ji}+k_{trm\,ji}\right)\left[M^i\right]\\+k_{tc\,jj}\,\lambda^j_{0,0}+k_{tc\,ji}\,\lambda^i_{0,0}+k_{tc0}\left[I^*\right]\end{array}\right\}\left[R^j_{n,m}\right]\end{array}\right)V \qquad (1)$$

$$\frac{dV\left[D^j_{n,m}\right]}{dt}=\left(k_{deact\,j}\left[R^j_{n,m}\right]\left[\left(X_2-Cu^{II}\right)L\right]-k_{act\,j}\left[D^j_{n,m}\right]\left[\left(X-Cu^{I}\right)L\right]\right)V \qquad (2)$$

$$\frac{dV\left[P_{n,m}\right]}{dt}=\left(\begin{array}{l}\left(k_{trm\,11}\left[M^1\right]+k_{trm\,12}\left[M^2\right]\right)\left[R^1_{n,m}\right]\\+\left(k_{trm\,21}\left[M^1\right]+k_{trm\,22}\left[M^2\right]\right)\left[R^2_{n,m}\right]\\+k_{tc12}\sum_{l=0}^{n-l}\sum_{r=0}^{m-r}\left[R^1_{n-l,m-r}\right]\left[R^2_{l,r}\right]\\+\left(\frac{1}{2}\right)k_{tc11}\sum_{l=0}^{n-l}\sum_{r=0}^{m-r}\left[R^1_{n-l,m-r}\right]\left[R^1_{l,r}\right]\\+\left(\frac{1}{2}\right)k_{tc22}\sum_{l=0}^{n-l}\sum_{r=0}^{m-r}\left[R^2_{n-l,m-r}\right]\left[R^2_{l,r}\right]\\+k_{tc10}\left[R^1_{n,m}\right]I^*+k_{tc20}\left[R^2_{n,m}\right]I^*\end{array}\right)V \qquad (3)$$

In these equations, $\delta_{x,y}$ is the Kronecker delta ($\delta_{x,y}=1$ if $x=y$ or 0 otherwise) and $\lambda^j_{0,0}$ is the moment of order (0,0) of the distribution of $R^j_{n,m}$. This moment is a particular case of the moment of order (a,b) of the distribution of $R^j_{n,m}$, defined as:

$$\lambda_{a,b}^{j} = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} n^{a} m^{b} \left[R_{n,m}^{j} \right] \tag{4}$$

Moments of the distributions of dormant and terminated polymer species may be also defined as:

$$\beta_{a,b}^{j} = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} n^{a} m^{b} \left[D_{n,m}^{j} \right] \tag{5}$$

$$\gamma_{a,b} = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} n^{a} m^{b} \left[P_{n,m} \right] \tag{6}$$

Given that the total polymer chain population is $\mathrm{CP}_{n,m} = \sum_{j=1}^{2} R_{n,m}^{j} + \sum_{j=1}^{2} D_{n,m}^{j} + P_{n,m}$, finding the bivariate MWD of CP requires solving Eqs. (1)-(3) for the infinite possible values of $n = 1,\ldots,\infty$ and $m = 1,\ldots,\infty$. Even though the maximum values of n and m may be truncated at given points N_{max} and M_{max}, the grid of points with dimensions ($N_{max}\times M_{max}$) is still usually extremely large. Here the pgf technique is used to process these equations to obtain a finite system. This modeling technique is based on transforming the mass balances of the polymeric species into the pgf domain, which results in a finite system, solving them and finally inverting the resulting pgf to recover the desired distribution. When applying the pgf transformation to Eqs. (1)-(3), the following pgf balances result [10]:

$$\frac{dV\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right)}{dt} = \begin{pmatrix} -k_{deact\,j}\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right)\left[\left(X_2 - Cu^{II}\right)L\right] \\ +k_{act\,j}\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right)\left[\left(X - Cu^{I}\right)L\right] \\ +\left\{\left(k_{trm\,jj}\,\lambda_{0,0}^{j} + k_{trm\,ij}\,\lambda_{0,0}^{i}\right)\left[M_j\right]\right\}\left(z_1\delta_{j,1} + z_2\delta_{j,2}\right) \\ +\left(k_{ij}\left[M^{j}\right] + k_{jj}\left[M^{j}\right]\right)\left(z_1\delta_{j,1} + z_2\delta_{j,2}\right)\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right) \\ +k_{0\,j}\left[I^{*}\right]\left[M^{j}\right]\left(z_1\delta_{j,1} + z_2\delta_{j,2}\right) \\ -\left\{\begin{matrix}\left(k_{jj} + k_{trm\,jj}\right)\left[M^{j}\right] + \left(k_{ji} + k_{trm\,ji}\right)\left[M^{i}\right] \\ +k_{tc\,jj}\,\lambda_{0,0}^{j} + k_{tc\,ji}\,\lambda_{0,0}^{i} + k_{tc0}\left[I^{*}\right]\end{matrix}\right\}\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right) \end{pmatrix} V \tag{7}$$

$$\frac{dV\left(\beta_{0,0}^{j}\varphi^{j}\left(z_1,z_2\right)\right)}{dt} = \begin{pmatrix} k_{deact\,j}\left(\lambda_{0,0}^{j}\phi^{j}\left(z_1,z_2\right)\right)\left[\left(X_2 - Cu^{II}\right)L\right] \\ -k_{act\,j}\left(\beta_{0,0}^{j}\varphi^{j}\left(z_1,z_2\right)\right)\left[\left(X - Cu^{I}\right)L\right] \end{pmatrix} V \tag{8}$$

$$\frac{dV\left(\gamma_{0,0}\theta\left(z_1,z_2\right)\right)}{dt}=\begin{pmatrix}\left(k_{trm\,11}\left[M^1\right]+k_{trm\,12}\left[M^2\right]\right)\left(\lambda_{0,0}^1\phi^1\left(z_1,z_2\right)\right)\\+\left(k_{trm\,21}\left[M^1\right]+k_{trm\,22}\left[M^2\right]\right)\left(\lambda_{0,0}^2\phi^2\left(z_1,z_2\right)\right)\\+k_{tc12}\left(\lambda_{0,0}^1\phi^1\left(z_1,z_2\right)\right)\left(\lambda_{0,0}^2\phi^2\left(z_1,z_2\right)\right)\\+\left(\frac{1}{2}\right)k_{tc11}\left(\lambda_{0,0}^1\phi^1\left(z_1,z_2\right)\right)^2\\+\left(\frac{1}{2}\right)k_{tc22}\left(\lambda_{0,0}^2\phi^2\left(z_1,z_2\right)\right)^2\\+k_{tc10}\left(\lambda_{0,0}^1\phi^1\left(z_1,z_2\right)\right)I^*+k_{tc20}\left(\lambda_{0,0}^2\phi^2\left(z_1,z_2\right)\right)I^*\end{pmatrix}V \qquad (9)$$

In Eqs. (7)-(9), $\emptyset^j(z_1,z_2)$, $\varphi^j(z_1,z_2)$ and $\theta(z_1,z_2)$ are the pgf transforms of $R_{n,m}^j$, $D_{n,m}^j$ and $P_{n,m}$, respectively, and z_1 and z_2 are the dummy variables of the pgfs. Besides,

$$\Phi\left(z_1,z_2\right)=\frac{\sum_{j=1}^{2}\left(\lambda_{0,0}^j\phi\left(z_1,z_2\right)\right)+\sum_{j=1}^{2}\left(\beta_{0,0}^j\gamma\left(z_1,z_2\right)\right)+\left(\gamma_{0,0}\theta\left(z_1,z_2\right)\right)}{\sum_{j=1}^{2}\lambda_{0,0}^j+\sum_{j=1}^{2}\beta_{0,0}^j+\gamma_{0,0}} \qquad (10)$$

is the pgf transform of $\mathrm{CP}_{n,m}$. Once the pgf balances are solved, the distribution $\mathrm{CP}_{n,m}$ is recovered from the transformed domain using the 2D IFG inversion method [11]:

$$\mathrm{CP}_{n,m}=\frac{1}{N_1N_2}\sum_{j=0}^{N_1-1}\sum_{k=0}^{N-1}\begin{pmatrix}f_{\mathrm{Re}}\left(j\frac{2\pi}{N_1},k\frac{2\pi}{N_2}\right)\cos\left(nj\frac{2\pi}{N_1}+mk\frac{2\pi}{N_2}\right)\\+f_{\mathrm{Im}}\left(j\frac{2\pi}{N_1},k\frac{2\pi}{N_2}\right)\sin\left(nj\frac{2\pi}{N_1}+mk\frac{2\pi}{N_2}\right)\end{pmatrix} \qquad (11)$$

In this equation, N_1 and N_2 are user-defined parameters, and $f_{Re}\left(j\frac{2\pi}{N_1},k\frac{2\pi}{N_2}\right)$ and $f_{Im}\left(j\frac{2\pi}{N_1},k\frac{2\pi}{N_2}\right)$ are the real and imaginary parts, respectively, of the complex pgf $\Phi\left(z_1=\exp\left(Ij\frac{2\pi}{N_1}\right),z_2=\exp\left(Ik\frac{2\pi}{N_2}\right)\right)$. The pgf balances of Eqs. (7)-(9) are parameterized for all the values of z_1 and z_2 for which the 2D IFG inversion method (Eq. (11)) needs pgf values. The total number of (z_1,z_2) pairs of values is [11]:

$$n_{ev}=\frac{N_1N_2}{2}+N_2+N_1-1 \qquad (12)$$

Note that, unlike Eqs. (1)-(3) for the different values of n and m, the triad of pgf balances Eqs. (7)-(9) for the different values of z_1 and z_2 are independent of each other.

In addition to the pgf balances, the model of the polymerization system is formed by the balances of the low-molecular-weight species (M^1, M^2, I-X, X-Cu^I)L, X_2-Cu^{II})L, I*, $Sn^{II}(EH)_2$, X-$Sn^{III}(EH)_2$, X-$Sn^{IV}(EH)_2$, reaction volume V, and moments $\lambda_{a,b}^j$, $\beta_{a,b}^j$ and $\gamma_{a,b}$ of orders $(a,b) = (0,0)$, (1,0), (0,1), (2,0), (1,1) and (2,0) required to compute the average molecular weights and copolymer composition [7]. Hence, the total number of balances for the different species is 50; these balances have to be solved for each pair of (z_1,z_2) values at which the inversion formula of Eq. (11) requires pgf evaluations. The sets of 50 balances for the different (z_1,z_2) pairs are independent of each other. The number of these independent blocks is given by n_{ev} in Eq. (12), and the total number of differential equations in the model is then $n_{ev}\times 50$.

3 Parallelization of the model execution

The version of the model employed in Part I of this work was much smaller in number of equations because it computed the overall, univariate MWD instead of the bivariate MWD, that is, $\mathrm{CP}_{l(l=n+m)}$ instead of $\mathrm{CP}_{n,m}$. The software gPROMS ModelBuilder was used because it is very convenient for solving parameter estimation problems and can handle a model of the size of Part I model. However, gPROMS ModelBuilder cannot support a model as large as the one of Part II of this work. Here, Julia was selected as the programming language [12]. This is a modern, free and open-source programming language, with high-level dynamic typing and specifically designed to obtain high performance in technical applications, numerical analysis, and scientific computing. The language combines several modern technologies from the field of programming and has native support for parallel computing. The process of parallelization of a certain code is quite straightforward compared to other languages where parallelization is not native and it is necessary to use other applications or libraries to do it.

The parallelization of the code involved two steps. The first one involved solving the independent blocks of the 50 model equations for each of the (z_1,z_2) pairs required by the inversion method. The execution of the solution process was parallelized using the built-in function *pmap* of Julia. This function maps the call to the numerical solver for the model equations to an array containing the (z_1,z_2) pairs in a parallel fashion among the CPU processors. The total set of pgf values was gathered from this parallel execution to be used as input to Eq. (11). Note that this equation gives the distribution for given values of n and m. The second step of the parallelization involved the calculation of $\mathrm{CP}_{n,m}$ for all (n,m) pairs at which it is desired to compute the distribution. This was accomplished mapping a function that computes Eq. (11) to an array containing the (n,m) pairs using the *pmap* function.

After obtaining $\mathrm{CP}_{n,m}$, this distribution was interpolated using built-in functions in Julia and processed to calculate the bivariate MWD-CCD of the copolymer, that is, $\mathrm{CP}_{l=n+m,c=n/(n+m)}$. Besides, the overall MWD ($\mathrm{CP}_l = \sum_c \mathrm{CP}_{l,c}$) and CCD ($\mathrm{CP}_c = \sum_l \mathrm{CP}_{l,c}$) were also computed.

4 Results and Discussion

The above mathematical model was used to calculate the bivariate MWD-CCD as well as the overall copolymer composition and molecular weight distributions for Experiments 3 and 6 reported in Part I of this work [8]. Parameters N_1 and N_2 of the 2D IFG inversion method were set at $N_1 = 2410$ $N_2 = 1950$ to satisfy the error control requirements of the inversion method [5]. This results in 2 352 904 equal, independent blocks of 50 pgf equations each. Therefore, the total model size is 2 352 904×50 = 117 645 200 differential equations. The solution of a model of this size, using an implicit DAE solver as required by the stiff system of equations, is infeasible in a regular PC. On the other hand, the parallelized implementation of the solution of the independent blocks in Julia, using a laptop equipped with an Intel Core i5-8250U processor and 12 GB RAM, demanded about 6 h CPU time. The grid of the MWD-CCD was divided into 150 points in each dimension so as to obtain a very smooth surface. The number of points of the distribution grid does not affect the number of differential equations of the model and has a small influence on the simulation time.

The final conversion is similar in Experiments 3 (75 %) and 6 (70 %). However, the ratio of monomer concentration/initiator concentration is higher in the second case (1649 for Exp. 3 and 3295 for Exp. 6.). Figs. 1 and 2 show the predicted bivariate MWD-CCD for these experiments. As expected, due to the higher ratio of monomer to initiator, the MWD-CCD of experiment 6 is shifted to higher molecular weights than in Experiment 6.

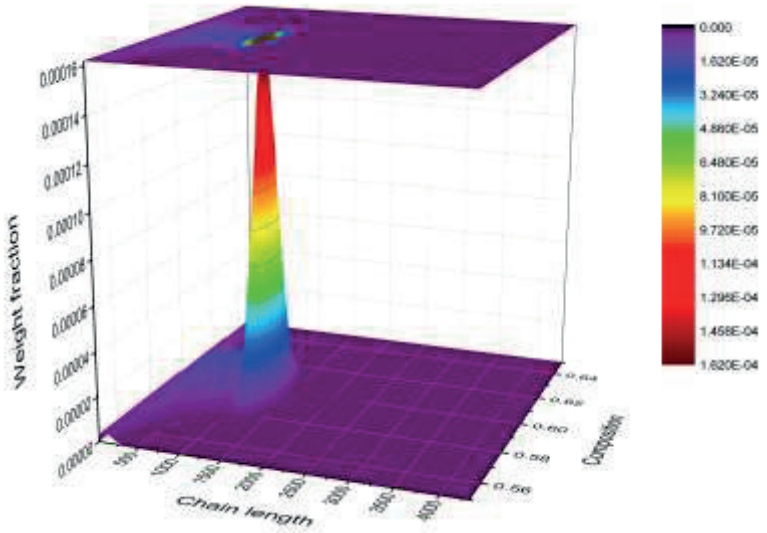

Fig. 1. MWD-CCD for Experiment 3.

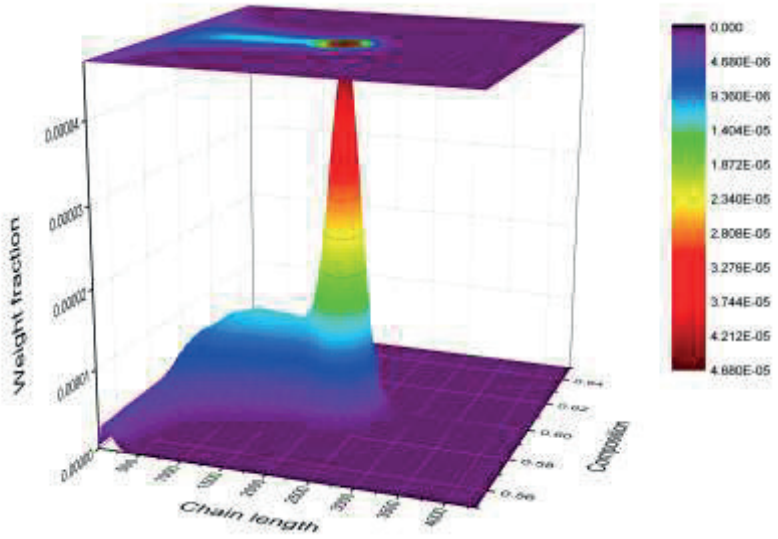

Fig. 2. MWD-CCD for Experiment 6.

These figures also show that the distribution in composition is narrow around the azeotropic value of 60 % for both experiments. On the other hand, the distribution in molecular weight is wider for experiment 6 presenting a long low-molecular-weight tail. These two features are also appreciated in the overall CCD and MWD presented in Figs. 3 and 4, respectively.

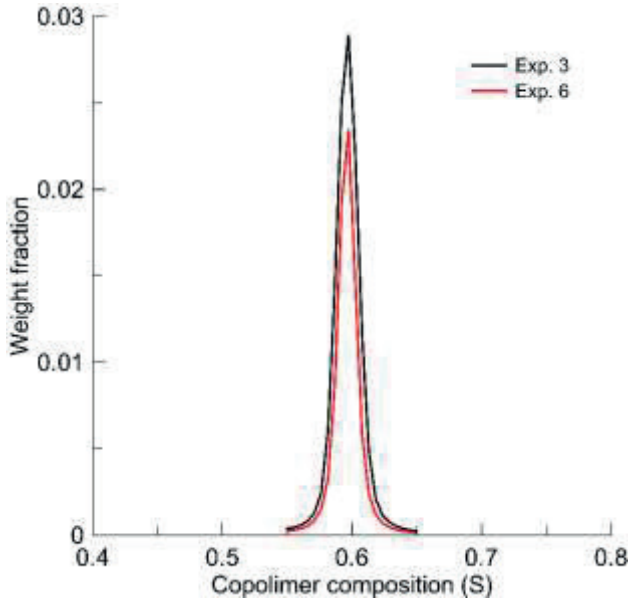

Fig. 3. Overall CCDs for experiments 3 and 6.

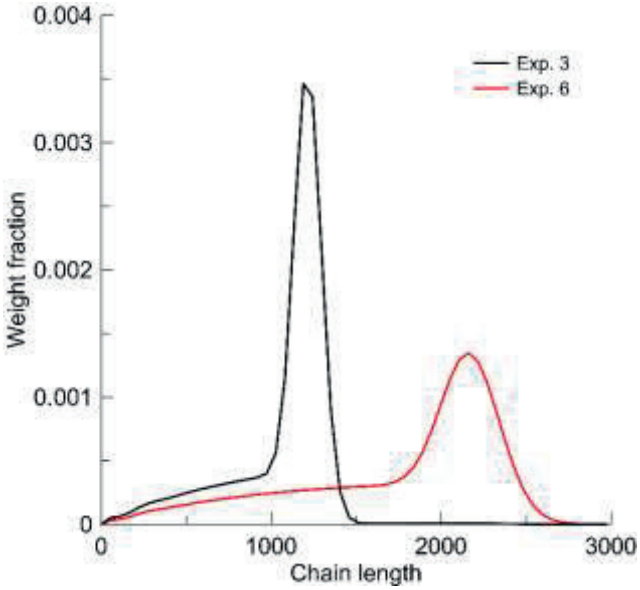

Fig. 4. Overall MWDs for experiments 3 and 6.

5 Conclusion

The pgf technique was successfully implemented to obtain the full 2D MWD-CCD of copolymers of SAN synthesized via ARGET-ATRP. The code developed in Julia allowed to significantly reduce the computational time while calculating a very detailed description of polymer molecular structure.

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ERP Integration with Performance Analytics: a Systematic Literature Review

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Abstract. Enterprise Resource Planning (ERP) systems have considerably become traditional as a part of organizations' IT systems in the last decades. ERP systems' research field have involved technology, project management and organizational learning since its birth. With the new big data era, ERP systems have been also progressively exposed to an extensive volume and variety of data in a short amount of time. Since then, a new study field regarding the linkage of these commercial systems with performance analytics to improve decision directions has emerged. Based on a systematic literature review methodology, the purpose of the present paper is to analyze recent research studies connecting ERP Systems to performance analytics. Proknow-C method was applied for a first iteration in Scopus. Results present a bibliographic portfolio analysis composed by 30 papers, being 70% journals and 30% conference papers. The interaction of both themes revealed that diverse environments have integrated analytics in ERP Systems to achieve smart management decisions. Although most studies have not reached many citations over time, the conjunction of both themes has been an important research issue worldwide. Author key-word analysis directed further research suggestions, identifying some possible extra key-words for ProKnow-C following iteration. The contribution of this paper is two-fold, a bibliometric analysis of the current scenario of ERP systems with performance analytics along with a summarized lessons learned of the present portfolio, connecting emergent technologies to cyber-security, organizational learning, hidden knowledge findings, active communication and multiple audit facilities as common output drivers for competitive performance.

Keywords: ERP Systems, Data Analytics, Performance Analytics, Decision-making, Systematic Literature Review.

1 Introduction

Organizations are increasingly investing in a competitive database with the capability to provide assertive decision-making processes. Investment in corporate management systems, also known as ERP Systems, aims to optimize operations, integrate internal departments and unite corporate databases. Over time, they have been associated to their ability to provide directions for decision support, since ERP became intensively exposed to expansive and diversified data structures in a fast environment and demanded the exploration of analytical features such as Business Intelligence (Holsap-

ple *et al.*, 2019). This connection between ERP and big data analytics has enabled faster decision making by providing near real-time statistical data and consistent dashboards of the organizations' current scenario as well as reporting historical events (Cadersaib *et al.*, 2018).

The scientific literature on ERP systems has focused on diverse fields of study since its birth in the end of the last century, exploring implementation challenges (Ismail and Zamre, 2015), implementation approaches (Nordin and Adegoke, 2015), ERP learning and performance (Plaza and Rohlf, 2008) and also technological, structural, behavioral changes and benefits experienced by organizations during ERP projects (Nwankpka, 2015). With the new technological field, some studies have investigated the connection between ERP Systems and performance analytics, exploring the benefits of ERP commercial packages on decision support (Shi and Wang, 2018; Holsapple *et al.*, 2019). Based on the described context, this paper proposes to explore both themes with a systematic literature review and answers the following research question: how is the current scientific scenario of ERP Systems integration with Performance Analytics?

The research question was used as a guidance for this investigation to find the linkages between ERP and performance analytics through a systematic literature review with Proknow-C method (Essnlin *et al.*, 2010).

2 Literature review

This chapter shows the literature review, starting with ERP Systems and Performance Analytics individual definitions, the chosen axes for this study.

2.1 ERP Systems

Historically, ERP Systems originated with MRP, Material Requirements Planning, in the early 1970s, which made it possible to calculate the amount of materials needed at each point in the production stage according to backlog orders. In the 80s, computers and the technological universe remarkably increased and, following this evolution, MRP I turned Material Resource Planning, commonly known as MRP II, providing complementary modules such as purchase control, shop floor control and capability resource planning. ERP is MRP II successor, because in addition to the manufacturing process, it encompasses the integrated planning of all other organizational departments (Correa *et al.*, 2011).

ERP Systems facilitate information flow among company activities, simplify processes and eliminate the need for parallel and inefficient controls. Benefits are not limited to process optimization, because they also improve risk management and business process security through transactions' traceability along with profiles consistent with their respective accesses and usage permissions (Nordin and Adegoke, 2015, Holsapple *et al*., 2019). Despite benefits diversity, ERP systems face complex implementation projects demanding rigid structural changes and companies are usually directed towards a department hierarchical view. The transition from a functional to a process-based view is a great challenge. However, with the proper implementation

approach, encompassing organizational cultural aspects, it is possible to increase successful cases (Al-mashari, 2003; Shi and Wang, 2018).

Technological developments have made it possible for organizations to use enterprise resource without infrastructure high costs. Cloud ERP has an extra advantage for being online with organizational data stored in the cloud. This measure not only guarantees the information security, but also allows the system to be accessed from anywhere. Thus, business performance indicators can be monitored more closely and provide efficient external sales. According to Gupta *et al*. (2018) cloud ERP has led to a constant creation of large data of structured and unstructured natures and consequently defended there has been a need to analyze such complex data sets within the integration of cloud ERP and big data predictive analytics.

2.2 Performance analytics

Big data analytics examines massive amounts of data to uncover hidden patterns, correlations and other analyses. Individual data can possibly be considered not extremely relevant for business strategies, however, big data analytics cases are progressively increasing, since a collection of spread individual data can provide competitive information, which any hidden knowledge can be found once collected into large volumes (Kim and Yu, 2015). Data analytics are also commonly divided into descriptive, diagnostic, predictive and prescriptive (Appelbaum *et al.*, 2017).

The term big data is commonly introduced as a technology for analyzing results from a large amount of structured and unstructured data set beyond the ability of reporting, saving and simulating decisions with traditional database administration resources (Holsapple *et al.,* 2019). Big Data term is also referred as a set capable of handling data generated within the 3V concept: variety, velocity and volume, structured or not with different formats. The challenge is directed to capture, treat and examine this mountain of information sources fast enough to provide strategic decisions. With the current technology, organizations have also used another famous approach for analytics named as business intelligence, an effort that is slower and gets forthwith analyzes with instantly reports (Nofal and Yusof, 2016).

Big data analytics is mostly related as an organizational tool with the ability to provide competitive knowledge for smart business decisions or even a system that supplies data architecture as an input and transforms information as output strategic guidelines (Olszak, 2016; Karimanzira and Rauschenbach, 2020).

Performance analytics has contributed to multidisciplinary environments, providing faster and more effective diagnostics in healthcare systems (Charleonnan *et al.*, 2016; Raglio *et al.*, 2020) and bringing competitive knowledge in organizational setting (Sabbeh, 2018; Jayadi *et al.*, 2019). However, big data analytics demand structured project plans involving cross-functional teams, innovative visualization technologies and leadership involvement to change management processes (Dutta and Bose, 2015). The present research investigates the current scientific scenario of data analytics linkage to ERP projects.

3 Research Design

The method selected to achieve the research purpose is Knowledge Development Process-Constructivist, also known as ProKnow-C (Ensslin *et al*., 2010). The process approach, simplified by Figure 1 with an overview of the main steps, consists on a complete structured process for bibliographic portfolio selection and literature analysis.

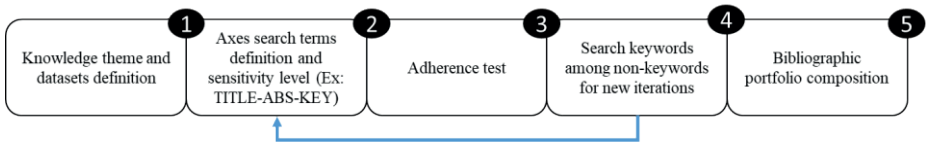


Figure 1. ProKnow-C main steps.

ProKnow-C methodology begins with the research theme definition within its field of study and the respective search databases. Secondly, search terms are defined to obtain the desired theme through axes' interaction along with search sensitivity level. An adherence test is following applied to test if search results matched its intended target. If the match is positively verified, the first bibliographic composition is available. The method involves extended iterations involving the search of new keywords in the first iteration's research papers for bibliographic composition continuously improvement.

The present study used ProKnow-C method to build exclusively the first literature composition of the both research themes: ERP Systems and Data analytics and limited Scopus database for this first iteration. Bibliometric analysis followed the sequential steps: publication over the years, citation overview, portfolio subject areas, predominant authors and finally, the key-word analysis.

4 Results

This chapter presents the research results, which is segmented by bibliographic portfolio composition and its sequential bibliographic analysis.

4.1 Bibliographic portfolio composition

The research themes used in the axes consisted of "ERP" and "analytics", respectively. The following search expression presented by Table 1.

Table 1. Search expression.

1st axis: ERP	Boolean Operator	2nd axis: analytics
("enterprise resource planning" OR "ERP system*" OR "Cloud ERP")	AND	("analytics" OR "business intelligence" OR "big data")

The search, made on July 14th at 11:25 a.m., was restricted for open access articles, Journals and Conferences, written in English and published between 2015 and 2019, considering exclusively Scopus database for bibliographic analysis. The search expression insertion in their respective database provided a preliminary result of 188 articles.

Table 2. Adherence test.

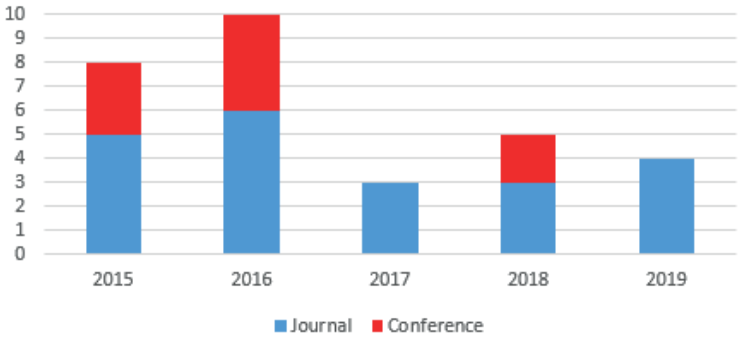
	Articles description
1	APPELBAUM, D., KOGAN, A., VASARHEYLI, M., YAN, Z.: Impact of business analytics and enterprise systems on managerial accounting", International Journal of Accounting Information Systems, v. 25 (No.March), pp. 29–44 (2017).
2	SHI, Z., WANG, G.: Integration of big-data ERP and business analytics (BA). Journal of High Technology Management Research, v.29 No., pp. 141-150 (2018).
3	DUSSOYE, H., CADERSAIB, Z.: Sentiment analytics framework integrating Twitter and Odoo ERP", 2017 International Conference on Infocom Technologies and Unmanned Systems: Trends and Future Directions, ICTUS 2017, v.2018(n.jan), pp. 145–151. (2018).
4	NYCZ, M., PÓLKOWSKI, Z.: The ERP system as a basic system for business analyses, Proceedings of the 2014 6th International Conference on Electronics, Computers and Artificial Intelligence, ECAI 2014, IEEE, pp. 63–66 (2015).
5	ROUHANI, S., MEHRI, M.: Does ERP have benefits on the business intelligence readiness? An empirical study. International Journal of Information Systems and Change Management, v. 8 (n.2), p. 81 (2016).

A considerable number of these articles were rejected for being book chapters, since the intended restriction was specified to limit Journals or Conferences studies and some others were also excluded due to availability, presenting as non-open access. On the next step, to verify if the selected search expression is adequate or if there was the need to find substitute terms that better represent the research themes, the recommendation of five articles reading was applied, as presented by Table 2.

Positive adherence by search expression could be observed, resulting in articles dealing with both research themes simultaneously, besides similar key words with the search expressions. Therefore, the raw bibliographic portfolio of 74 papers was originated. Sequentially, the refinement phase was applied reading the 74 articles titles and abstracts discarding 44 considered either non-aligned or not specifically addressing both topics, resulting in 30 final articles presented by Appendix Section.

4.2 Bibliographic portfolio analysis

The selected portfolio is predominantly composed by journals, counting 70% with the other remaining 30% composed by international conferences. In addition, bibliographic portfolio over the years, exhibited by Figure 2, reveals a noticeable stronger impact in the researched field in 2015 and 2016 comparing to other yeas.



Year	2015	2016	2017	2018	2019	Total	% Total
Journal	5	6	3	3	4	21	70%
Conference	3	4	0	2	0	9	30%

Figure 2. Bibliographic portfolio over the years.

Regarding scientific relevance, it was perceived few citation quantity, with most of the papers counting less than five citations. Figure 3 indicates only two articles have exceeded 20 citations. One possible explanation for the low impact is search restriction for studies written between 2015 and 2019 and therefore time exposition is still relatively short.

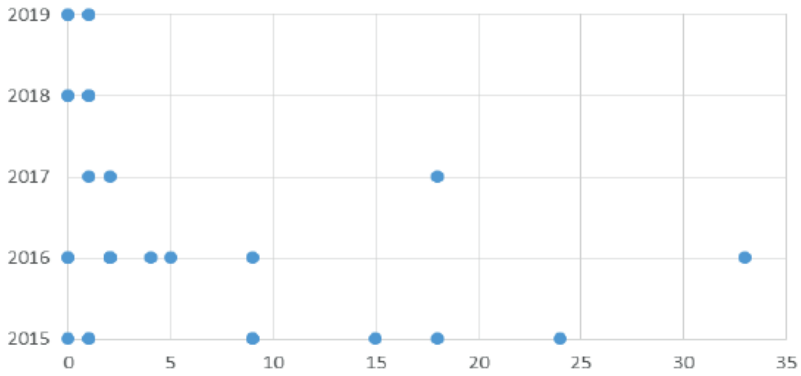


Figure 3. Citation overview.

Sequentially examining scientific relevance, the journals composed in the portfolio were also analyzed according to their respective SJR indicators, Table 3. There is no specific journal dominating the bibliographic portfolio composition, presenting consistent diversity. However, some journals are high rated regarding their SJR qualifications, increasing the portfolio scientific value.

Table 3. SJR indicators.

Journal	SJR
Journal of Information Technology	2,1
International Journal of Operations and Production Management	2,1
Journal of Business Research	1,7
Computers in Industry	1,2
International Journal of Advanced Manufacturing Technology	1,0
Computers and Electronics in Agriculture	1,0
Management Decision	0,7
Information Processing in Agriculture	0,6
Business Process Management Journal	0,6
Information Systems Management	0,5
International Journal of Accounting Information Systems	0,5
Information Technology and Management	0,4
Journal of Supercomputing	0,4
Kybernetes	0,3
International Journal of Business Information Systems	0,3
Journal of High Technology Management Research	0,3
Library Hi Tech News	0,3
International Journal of Software Engineering and its Applications	0,2
International Journal of Information Systems and Change Management	0,1
International Journal of Internet Manufacturing and Services	0,1
International Journal of Intelligent Information and Database Systems	0,1

The remaining conference papers in portfolio composition are also diverse, counting International Conference on Enterprise Systems, International Advanced Computing Conference, Global Conference on Communication Technologies and many others involving industrial engineering and computational intelligence.

Examining the studies' scope classified by subject areas presented by Figure 4, it can be observed that most of papers addressing data analytics with ERP Systems deal with Computer Science (34,4%), Business, Management and Accounting (17,2%) and Decision Sciences impacts specifically (15,6%) research fields. The specificity and diversity involving the remaining subject areas can be explained by the specificity of some contributions involving agricultural, social sciences and energy environments.

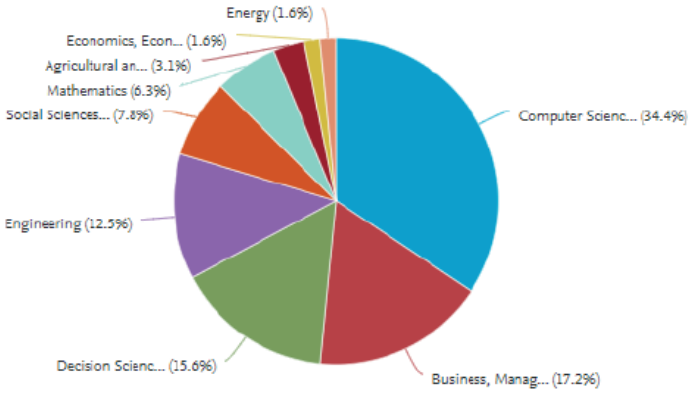


Figure 4. Portfolio subject areas.

In respect of the authorship 83 different authors appeared. Of these, only a single author had incidence of two publications in the portfolio, the Portuguese management researcher Oliveira T., and all the remaining stayed with one frequency. Analyzing the portfolio regarding their country, as exhibited by Figure 5, it is perceptible a domain in India, although United States remained a single paper behind and Germany together with Taiwan had a noticeable contribution. This fact indicates that the conjunction of the two themes have been researched worldwide by all continents.

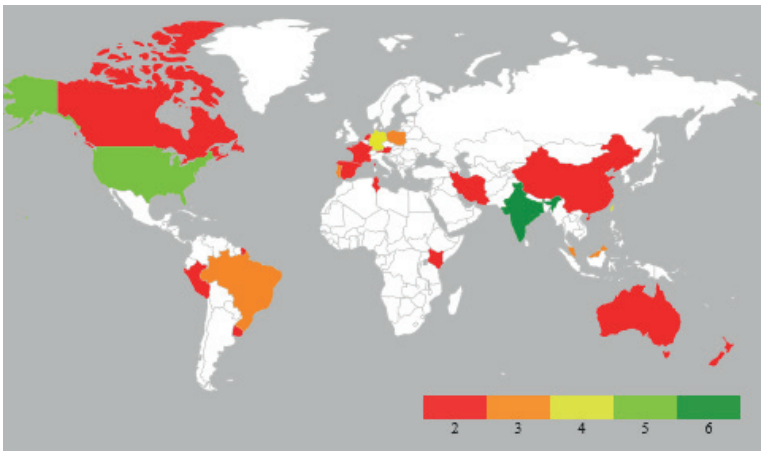


Figure 5. Portfolio geographic heat map.

Author keywords' analysis, Figure 6, revealed most of the common key-words among portfolio authors were defined by search axes.

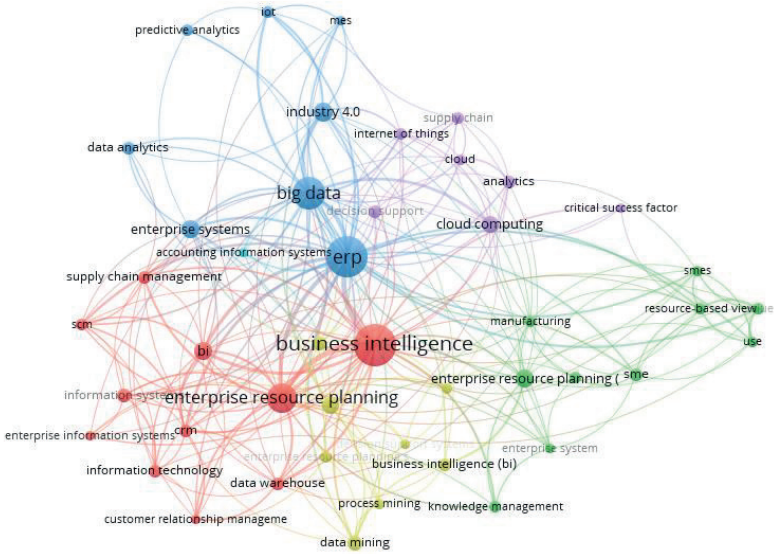


Figure 6. Author keyword analysis.

Some of non-keywords among author keywords, such as data mining, cloud computing and data warehouse, are considered relatively important for a second search iteration, following Proknow-C method steps.

4.3 Lessons Learned Portfolio Summary

The present bibliographic portfolio composition reveals diversity not only among study centers, authors and multi-sector organizations, but also of the emergent technologies connected to ERP systems. Figure 7 presents some contributions identified on ProKnow-C first iteration.

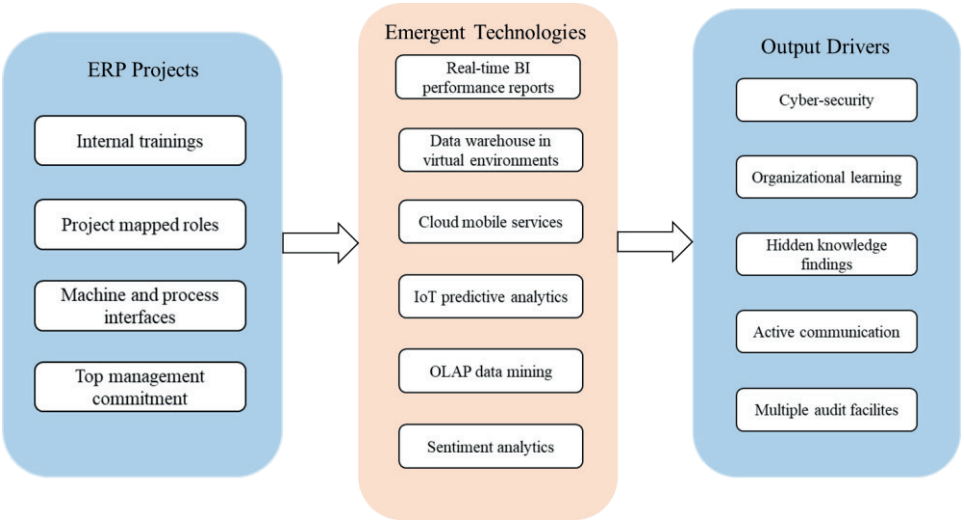


Figure 7. Summary of lessons learned.

The interaction of both axes presents a summary of common best practices among ERP projects, such as internal trainings, mapped roles, process interfaces and top management involvement. Regarding emergent technologies, business intelligence reports are the most predominant object of study (Kim and Yu, 2015; Shi and Wang, 2018, Ranjan *et al.*, 2017). On the other hand, some approaches are more unusual with distinct perspectives, revealing new trends, such as sentiment analytics using microblogging to find social media feelings (Dussoye and Cadersaib, 2018) and IoT predictive analytics for aquaponics management (Karimanzira and Rauschenbach, 2020).

Summary of lessons learned also connects the emergent technologies to competitive outputs that have supported organizations to find hidden knowledge (Kim and Yu, 2015; Nycz and Pólkowsky, 2015; Shi and Wang, 2018), build cyber-security (Tai *et al.*, 2016), organizational learning (Labonte-LeMoyne, 2017), active communication (Nofal and Yusof, 2016) and multiple audit facilities (Werner and Gehrke, 2015; Gambetta *et al.*, 2016).

5 Conclusion

The present systematic literature review have successfully achieved a first iteration with assertive keywords that brought relevant recent papers interacting ERP Systems with data analytics. The following step is to continue Proknow-C method trying new keywords among non-keywords to extend bibliographic portfolio composition, since this study was limited to a single first step in Proknow-C process. Another limitation is related to search restriction to Scopus, since the present first iteration can possibly be extended once new databases are included.

The interaction of performance analytics term relating to ERP Systems have reached distinct areas and contributed to management decisions for near real-time data analysis in medical institutions (Kim and Yu, 2015), bank's audit (Gambetta *et al.*, 2016), manufacturing enterprises (Ranjan *et al.*, 2017) and agriculture environment (Junior *et al.*, 2019; Karimanzira and Rauschenbach, 2019). Curiously, even polish water parks (Nycz and Pólkowsky, 2015) have been improving decision-making integrating analytics with their ERP systems.

Regarding analytics and some of its classifications, some papers specify their studies, such as sentiment analytics (Dussoye and Cadersaib, 2018) or predictive analytics (Karimanzira and Rauschenbach, 2019) while others explore the theme without explicitly classifying along their studies. The main contribution of this paper consisted on identifying the diversity integration of ERP systems with performance analytics. Common emergent technologies were listed in lessons learned, connecting to cybersecurity, organizational learning, hidden knowledge findings, active communication and multiple audit facilities as performance output drivers. This briefly summarized interrelationship can be linked to a further research with a more extensive content analysis. Complementarily, a secondary study could also enhance additional relevance and dialogue to recent research, such as the effects of capabilities and policies of strategic decision areas on manufacturing high performance (Okoshi *et al*., 2019) or even management frameworks (Giordani da Silveira *et al*., 2018), since performance analytics has brought a new scenario of management.

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Appendices – List of bibliographic portfolio composition

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Avaliação de Interoperabilidade Empresarial: Uma revisão sistemática da literatura

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Abstract. Interoperability is a necessity for organizations to achieve their business objectives and remain in the market. For this, it must be continuously measured and improved. This paper aims to show a systematic literature review about interoperability assessment, using the methodology Proknow-C, with the objective of raising the main aspects of the researchs. Two phases of the method were made. On the first phase was made the selection of the bibliographic portfolio (BP), were found 21 papers related to the subject. In sequence on the second phase was made a bibliometric analysis. The more expressive areas on the BP are the engineering and computer science. Is perceived a preponderance from studies focused on supply chain and government area assessment.

Keywords: Enterprise Interoperability Assessment, Organizational interoperability, systematic literature review, Proknow-C.

1 Introdução

Atualmente, para atuarem de maneira competitiva, as empresas precisam monitorar em tempo real seus recursos e controlar com eficiência suas operações, reagindo com rapidez ao mercado dinâmico [1]. Outro fator que determina o sucesso das organizações no mercado globalizado é a sua capacidade de desenvolver parcerias. Para isso é importante a capacidade de comunicação e interação [2].

Neste sentido, a concepção de interoperabilidade se apresenta como um meio para melhorar a comunicação e interação, tanto interna, como também entre as organizações. Interoperabilidade tem conceito amplo e com muitas definições [2]. O Institute of Electrical and Electronics Engineers [3] define como a "capacidade de dois ou mais sistemas ou elementos trocarem informações entre si e usarem as informações trocadas".

Um fator que impede a interoperabilidade são as barreiras, definidas por Chen [4] como incompatibilidades de vários tipos e em vários níveis da empresa. Para evitar problemas de interoperabilidade as empresas devem conhecer as barreiras existentes, para desenvolver soluções e removê-las [4]. Neste contexto, a avaliação da interoperabilidade pode beneficiar as organizações [5].

Na literatura, há diversos modelos de avaliação de interoperabilidade com diferentes abordagens, escalas e aplicações. O objetivo deste estudo é apresentar uma visão geral dos modelos existentes por meio de uma revisão sistemática da literatura utilizando o método ProKnow-C.

2. Referencial Teórico

2.1. Interoperabilidade

A European Interoperability Framework in the eGovernment domain [6] define três tipos de interoperabilidade: a semântica, a técnica e a organizacional. Marcondes e Sayão [7] acrescentam mais três tipos: a política, a internacional e a legal. Alguns autores chamam os tipos de camadas da interoperabilidade.

A interoperabilidade apresenta três dimensões. A primeira são as barreiras, classificadas em três tipos: Conceitual (diferenças sintáticas e semânticas das informações a serem trocadas), Tecnológica (incompatibilidade de tecnologias da informação) e Organizacional (incompatibilidade das estruturas da organização). A segunda dimensão se refere às diferentes áreas de preocupação da empresa (dados, serviço, processo, negócios). A terceira são as abordagens, que consistem nas diferentes maneiras pelas quais as barreiras podem ser removidas (integrada, unificada e federada) [4].

O conhecimento sobre interoperabilidade fornece soluções para remover as barreiras em quatro áreas específicas: Dados (encontrar e compartilhar informações provenientes de bases heterogêneas e máquinas diferentes); Serviço (identificar, compor e fazer funcionar juntos vários serviços); Processo (fazer com que vários processos funcionem juntos) e Negócios (trabalhar de maneira harmonizada nos níveis da organização, para que os negócios possam ser desenvolvidos e compartilhados entre empresas) [4].

2.2. Avaliação de desempenho organizacional

O desempenho é abordado por muitos campos do conhecimento, tais como, contabilidade, recursos humanos, marketing entre outros. Avaliação deixou de olhar apenas para medidas de desempenho financeiro e de produtividade, passou também a medir aspectos qualitativos e intangíveis de desempenho [8].

Definir corretamente os indicadores que refletem os objetivos da organização é um desafio, pois os indicadores de desempenho assumem papel central, por se apresentarem como instrumentos capazes de fornecer informações para o processo de tomada de decisão [9].

A literatura apresenta diversos métodos para a medição de desempenho das organizações entre os mais conhecidos estão o Balanced Scorecard (BSC) [39], Performance Prism [40], ECOGRAI [41] entre outros.

2.2. Avaliação da Interoperabilidade

Os modelos para avaliar a interoperabilidade existentes se propõem a medir a potencialidade, compatibilidade e desempenho. A avaliação da potencialidade mede a capacidade da organização se adaptar e superar possíveis barreiras, ao interagir com um parceiro em potencial.

A avaliação de compatibilidade analisa o estado atual dos sistemas envolvidos, para identificar conflitos que causam, ou podem causar problemas. A avaliação de des-

empenho mede os custos para a implementação de aplicativos interoperáveis e a qualidade durante todo o tempo de execução [22].

A avaliação de potencialidade está ligada a modelos de maturidade, pois a maturidade pode ser entendida como potencial de interoperação [22]. Alguns exemplos são o Extended Enterprise Architecture Maturity Model, o Organisational Interoperability Maturity Model e o Enterprise Interoperability Maturity Model [10].

Com relação à compatibilidade o INTEROP framework avalia a interoperabilidade nas três dimensões: as barreiras, preocupações e abordagens [11]. Outros modelos conhecidos são o ERISA [42], IDEAS [43] ATHENA framework[44].

2 Metodologia

Este estudo pode ser classificado como de natureza conceitual aplicado, por seu interesse em aplicação prática. Quanto aos objetivos é exploratório, pois busca evidenciar o problema de pesquisa utilizando pesquisa bibliográfica. A abordagem é qualitativa e quantitativa e o procedimento utilizado foi a pesquisa bibliográfica [12]

Para a realização da revisão bibliográfica foi utilizado o ProKnow-C, metodologia desenvolvida por Ensslin e Ensslin [13]. O método é composto por quatro etapas: (1) Seleção do Portfólio Bibliográfico (PB), (2) Análise Bibliométrica, (3) Análise sistêmica, (4) Identificação de uma pergunta de pesquisa e do objetivo para futuras pesquisas [13].

O Proknow-C apresenta um processo estruturado para a construção de conhecimento, fornece um panorama da área investigada e aponta questões para novos estudos [13]. Foram realizadas duas etapas do Proknow-C: (1) Seleção do Portfólio Bibliográfico, (2) Análise Bibliométrica.

3.1. Etapa 1 - Seleção do Portfólio

Foram delimitados dois eixos de estudo “interoperabilidade” e “avaliação de desempenho”, sendo que as palavras-chave destes eixos foram usadas em uma pesquisa preliminar na base de artigos Science Direct para verificar a aderência.

Foram encontradas novas palavras-chave e incluídas na pesquisa. As bases utilizadas foram Science Direct, Emerald Insight e Scopus. A Tabela 1 apresenta a definição final das palavras-chave.

Tabela 1. Eixos da pesquisa e Palavras-chave

Eixo I: Interoperabilidade	Eixo II: Indicadores
Enterprise Interoperability Assessment	*Performance Measurement*
Interoperability Assessment	*Performance Indicators*
Business interoperability	*Performance Evaluation*
Organizational interoperability	*Performance Assessment*

3.2. Etapa 2 - Análise Bibliométrica

A etapa de análise bibliométrica dos artigos consiste em um levantamento e análise quantitativa das características do PB de artigos da etapa anterior, com objetivo de evidenciar as informações relevantes para a área de estudo [13].

A análise bibliográfica foi realizada em seis passos: (1) Levantar os periódicos nos quais os artigos foram publicados e verificar o grau relevância destes, (2) Estimar o grau de relevância dos artigos, (3) Estimar o grau de relevância dos autores, (4) Verificar as palavras-chave mais utilizada e verificar a relação entre elas, (5) Analisar a referência dos artigos do PB e (6) Analisar a relevância dos artigos para o PB.

3 Resultados

Os artigos encontrados foram filtrados de 2011 a 2020 e exportados para análise para o EndNote Web. Foram encontrados 64 artigos. Destes foram excluídos três por duplicação, 19 após a leitura dos títulos e 16 após a leitura dos resumos. Dos 26 artigos lidos, 21 contemplam o objetivo da pesquisa, a Tabela 2 apresenta os artigos que compõem o PB.

Tabela 2. Portfólio Bibliográfico

Nº	Título	Cit	Ref.
1	*Organisational interoperability characterisation and evaluation using enterprise modelling and graph theory*	3	[16]
2	*An agent-based model for analyzing the impact of business interoperability on the performance of cooperative industrial networks*	10	[17]
3	*Methodology for prior evaluation of interoperability*	7	[18]
4	*A methodology for interoperability evaluation in supply chains based on causal performance measurement models*	3	[19]
5	*A methodology for the evaluation of interoperability improvements in inter-enterprises collaboration based on causal performance measurement models*	21	[20]
6	*Interoperability assessment: A systematic literature review*	18	[21]
7	*How to measure interoperability: Concept and approach*	12	[2]
8	*A contribution of system theory to sustainable enterprise interoperability science base*	55	[22]
9	*Sustainable interoperability: The future of Internet based industrial enterprises*	60	[23]
10	*Reconceptualizing measuring, benchmarking for improving interoperability in smart ecosystems: The effect of ubiquitous data and crowdsourcing*	45	[24]
11	*A critical survey of selected government interoperability frameworks*	39	[25]
12	*Impact evaluation of interoperability decision variables on P2P collaboration*	1	[26]
13	*The business interoperability quotient measurement model*	45	[27]
14	*Interoperability assessment in context-aware systems for intelligent transport*	0	[28]
15	*Re-design of an Interoperable Buyer-seller Automotive Relationship Aided by Computer Simulation*	1	[29]
16	*The Business Interoperability Decomposition Framework to analyse buyer-supplier dyads*	1	[30]
17	*Industry 4.0: A survey on technologies, applications and open research issues*	88	[31]
18	*Performance evaluation of collaboration in the design process: Using interoperability measurement*	19	[32]
19	*A fuzzy rule-based system to assess e-government technical interoperability*	12	[33]

20	*Supporting the evolution and interoperability of organisational models with e-learning technologies*	10	[34]
21	*Learning for Sustainable Organisational Interoperability*	6	[35]

3.1. Análise Bibliométrica

Dos 21 artigos analisados, 18 foram publicados em periódicos e 3 em anais de eventos. Nesta etapa foi levantado o nome dos periódicos, a quantidade de artigos que cada um tinha no PB e o fator de impacto de cada periódico.

Pode se perceber um predomínio de publicações no Computers in Industry, que concentra 7 publicações. Em segundo lugar, mas bem menos expressivo o Transforming Government: People, Process and Policy, com duas publicações. Os demais tiveram um artigo cada. A Figura 1 apresenta gráfico com números de artigos por periódico no PB.

O fator de impacto foi consultado no Journal Citation Reports (JCR). O índice é publicado anualmente, com dados das publicações do ano anterior e citações dos dois anos imediatamente anteriores. A grande parte dos artigos não constava na base, por não serem periódicos indexados a Web of Science. O periódico de maior fator de impacto foi o Computers in Industry, com 4,769.

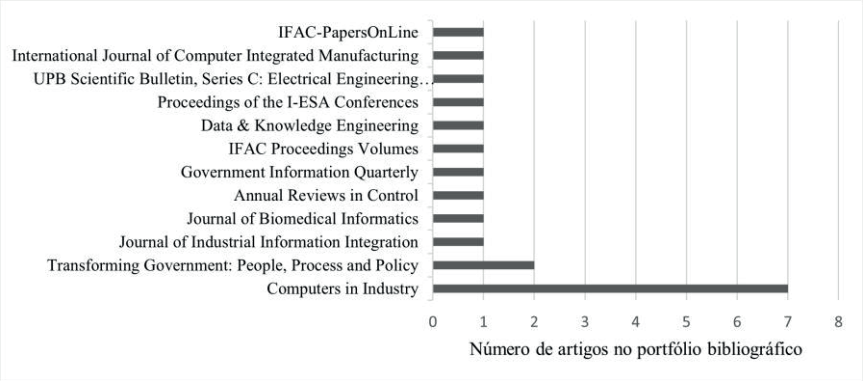

Fig. 1. Números de artigos por periódico

Para a estimativa da relevância acadêmica dos artigos do PB foi considerado o número de citações indicados no Google Acadêmico e na base Scopus. No Google acadêmico os artigos do PB apresentam um total de 1249 e na Scopus 707.

O artigo "Industry 4.0: A survey on technologies, applications and open research issues" possui o número de citação bem acima dos demais, possuindo 886 citações (Google acadêmico) e 492 (Scopus). Três artigos tiveram apenas uma citação, e um artigo não teve nenhuma citação, no entanto este artigo é de 2019.

O ano com mais publicações no PB bibliográfico foi 2012, com 5 publicações. Não constam publicações no ano de 2013.

Quanto a citação dos artigos do PB, o ano com mais citações foi 2019 com 565, no entanto esse número está um pouco distorcido devido ao artigo do Lu, Y. que tem citações muito acima dos demais, sendo responsável por 499 citações em 2019.

Os 21 artigos do PB contaram com a participação de 40 autores. O autor com mais artigos, foi Ducq, Y. com 6 publicações, seguido de Grilo, A. com 5. A Figura 2 ilustra o gráfico com a quantidade de artigo por autores. Os demais autores, que possuem um artigo, não constam no gráfico.

O índice h é uma maneira de medir a produtividade e o impacto das publicações acumuladas de um pesquisador. Os autores terão o índice h, se h de seus trabalhos tiverem pelo menos h citações, por exemplo, um autor terá índice h=2, se possuir 2 artigos, com pelo menos 2 citações [36]. O autor com maior índice h foi o Janssen, M., com h=39 e 433 publicações. A Figura 3 apresenta um gráfico com os autores que apresentam maiores índice h no PB.

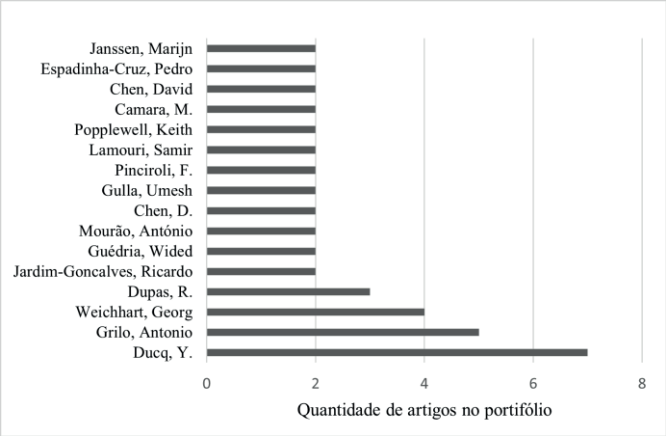

Fig. 2. Número de artigos do PB por autor

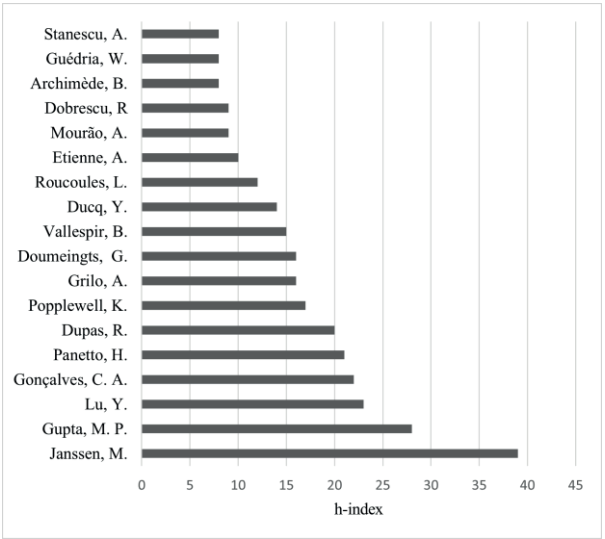

Fig. 3. Índice h dos autores do PB

A análise apontou para a ocorrência de 95 palavras-chave. Destas as mais frequentes foram Interoperability e Enterprise interoperability, as duas com cinco ocorrências. As palavras-chave mais utilizadas estão indicadas no gráfico da Figura 4 e a sua relação estão apresentadas na Figura 5.

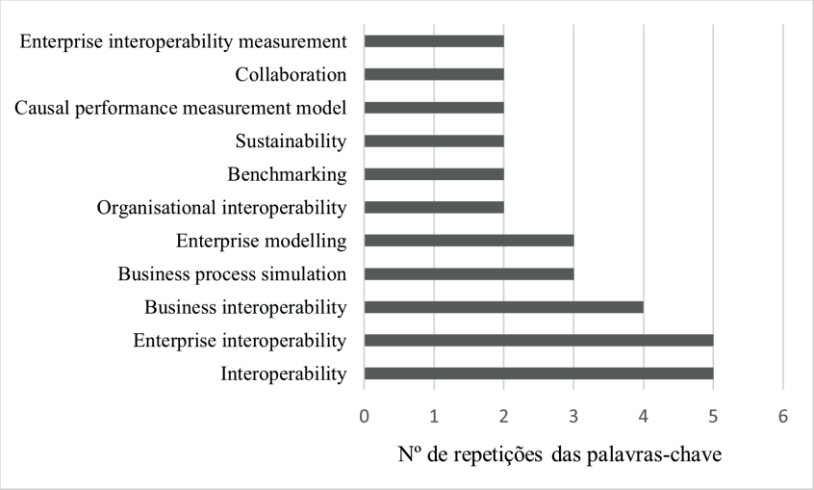

Fig. 4. Quantidade de ocorrência das palavras-chave

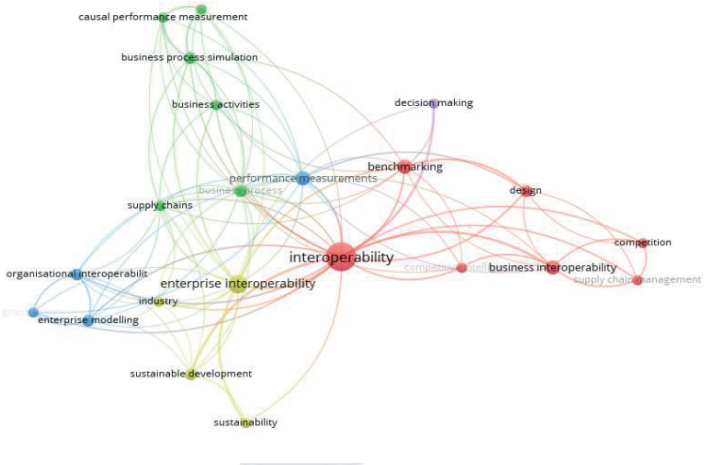

Fig. 5. Relação entre as palavras-chave utilizadas no artigo do PB

3.2.5 Análise da referência dos artigos do portfólio

Os artigos do PB analisado citam 1439 autores, deste o mais citado é Chen, D. com 68 citações, seguido de Jardim, G. R. com 34. A Figura 6 apresenta um gráfico com os autores mais citados do PB e a Figura 7 a relação entre estes autores citados.

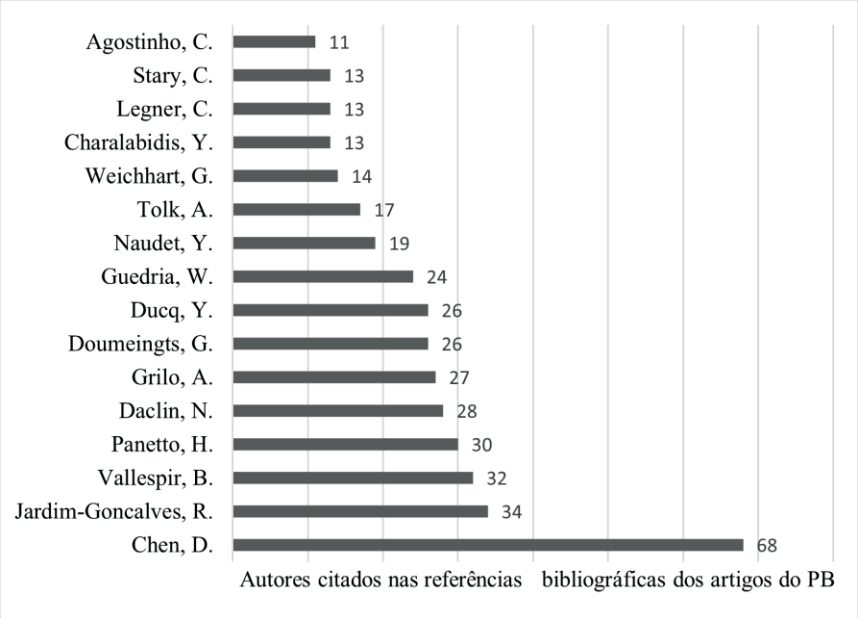

Fig. 6. Artigos citados nas referências do PB

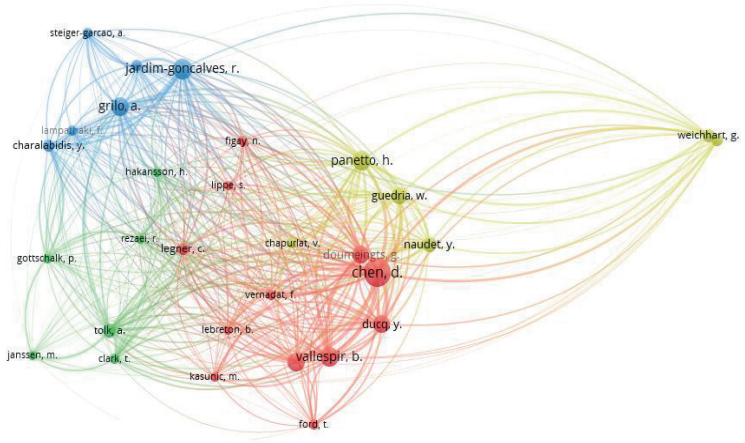

Fig. 7. Relação entre os autores citados nas referências dos artigos do PB

O país com maior quantidade de publicações foi a França, seguido de Portugal com 9 e 5 artigos respectivamente. O Brasil possui uma publicação, o artigo 19. As áreas de estudo predominantes são a engenharia e ciência da computação.

Os artigos destaques foram o 9, o 8 e o 10, respectivamente com 46, 35 e 31 citações na base Scopus. O artigo 8 foi um artigo destaque realizado por um autor

destaque, o autor deste artigo mais citado no PB foi o Chen com 68 citações. A Figura 8 apresenta um gráfico de dispersão para evidenciar a relevância dos artigos do PB, o artigo 17 não foi incluído no gráfico, pois ele possui o número de citações muito superior aos demais e distorceria a visualização dos dados, além disso, o artigo não foi citado nos demais artigos do PB.

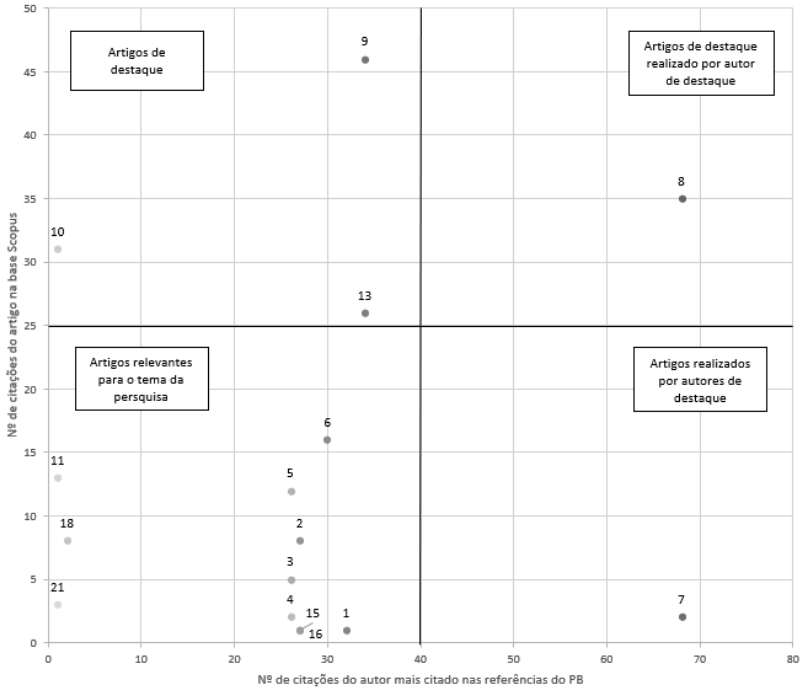

Fig. 8 Artigos com maior destaque no PB

3.4. Discussão sobre os artigos do portfólio bibliográfico

A interoperação em redes de colaboração trouxe vantagens competitivas para as empresas e tornou-se um ponto crítico para alcançar os objetivos do negócio [38]. No PB, 6 artigos apresentam modelos voltados a medir e melhorar a interoperabilidade entre empresas parceiras. Os estudos 3, 4, 15 e 16 seus modelos são aplicados à cadeia de suprimentos. E os artigos 2 e 5 apresentam estudos voltados à empresas que cooperam.

Os governos de diversos lugares também estão adotando estratégias para alcançar a interoperabilidade, para enfrentar o problema da heterogeneidade entre sistemas de informação do governo [25]. Nessa perspectiva o artigo 10 apresenta modelo de medição de interoperabilidade em governo inteligente. O artigo 11 propõe uma estrutura analítica para avaliação, classificação e comparação qualitativa dos Frameworks de interoperabilidade governamental. O artigo 19 propõe um sistema para avaliar o nível de maturidade de interoperabilidade técnica do governo.

Outro tema abordado é a interoperabilidade contribuindo para a sustentabilidade das organizações. Nesse sentido o artigo 8 discute como a teoria dos sistemas, aplicada à sistema de sistemas, é capaz de apoiar o desenvolvimento da interoperabilidade empresarial sustentável. Os artigos 20 e 21 abordam conceitos de interoperabilidade para ajudar a alcançar níveis de sustentabilidade no contexto de sistemas adaptativos complexos.

Alguns artigos apresentam seus estudos da avaliação de interoperabilidade organizacional de forma ampla, sem especificar um grupo específico, como é o caso do artigo 1 e 13. O artigo 16 propõe uma estrutura para apoiar a análise das condições de interoperabilidade na relação comprador-fornecedor.

Os artigos apresentam variados contextos e propósitos. No artigo 1 o foco da avaliação está na detecção da falta de interoperabilidade e avaliação dos esforços necessário atingir ou manter o nível de interoperabilidade alvo.

O artigo 2 tem o objetivo de simular a maneira pela qual as empresas interoperam em redes industriais cooperativas e como distância entre o nível real e o necessário de interoperabilidade podem afetar o desempenho dessas empresas.

Nos artigos 3, 4 e 5 os autores buscam avaliar como os investimentos em interoperabilidade participam na obtenção dos objetivos da empresa. O artigo 13 apresenta modelo BIQMM - Medição de Quociente de Interoperabilidade de Negócios baseado em pesquisa como ATHENA, ECOLEAD e COIN, buscando capturar os fatores responsáveis pela interoperabilidade. No artigo 14 os autores apresentam um conjunto de características que podem apoiar a tomada de decisão e a avaliação da interoperabilidade no domínio de sistemas sensíveis ao contexto aplicado à gestão de sistemas de transporte inteligentes.

No artigo 17 os autores realizam uma revisão abrangente sobre a indústria 4.0, mesmo que a avaliação de interoperabilidade não seja o tema central do artigo, foi mantido no no PB, pois dedica boa parte ao tema. Os autores descrevem questões críticas da interoperabilidade da Indústria 4.0, propõem um quadro conceitual e apresentam alguns frameworks para avaliação de interoperabilidade.

Quanto aos métodos e ferramentas, os estudos utilizam variados. Os artigos 7 e 9 apresentam uma revisão literatura sobre avaliação da interoperabilidade e o artigo 6 exibe uma revisão sistemática da literatura. Dos 21 artigos do PB 12 apresentam estudo de caso. O artigo 1 utiliza modelagem corporativa, gráfico verificação de teoria e regras. O artigo 2, 5, 12 e 15 realiza simulação. Os artigos 3 e 8 usam a metodologia GRAI. O artigo 19 utiliza regras Fuzzy no modelo proposto.

4 Considerações Finais

Este trabalho teve por objetivo apresentar informações relevantes para área de pesquisa de avaliação de interoperabilidade. Por meio da aplicação do Proknow-C, se chegou a um PB com 21 artigos relevantes.

A análise bibliométrica dos artigos do PB apontou os seguintes resultados: (i) o periódico mais destacado para o tema é o Computers in Industry, com 7 artigos no PB, o periódico também é o de maior fator de impacto com JCR 4,769; (ii) o artigo 17 é o com maior reconhecimento científico com 886 citações (Google acadêmico) e 492 (Scopus) (iii) o autor com maior índice h é o Janssen, M., com h=39 e 433 publi-

cações; (iv) A palavra-chave mais usada foi Interoperability e Enterprise interoperability, ambas com cinco ocorrências; (v) O autor mais citado nas referências foi o Chen, D. com 68 citações (vi) o artigo mais relevante para o PB é o 8.

O artigo 8 é apontado como o mais relevante do PB para o estudo, pois o artigo e o autor são destaques quanto a quantidade de citações. O artigo analisa a interoperabilidade considerando a teoria de sistemas, considera problemas de interoperabilidade entre diferentes tipos de sistemas (ecológicos, econômicos, de pesquisa etc). O estudo propõe um modelo de avaliação e aplica em um estudo de caso.

Entre os artigos encontrados 3 se dedicam a revisão da literatura apresentando diversos métodos de avaliação de interoperabilidade. Dos artigos do PB 11 propõem modelos de avaliação, o que manifesta a importância de criar critérios de avaliação da interoperabilidade. Outro aspecto importante foi à aplicação prática dos métodos, pois 12 artigos apresentam estudo de caso e 1 demonstra em uma situação hipotética deixando como lacuna a aplicação.

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Evaluación de la incorporación de residuos de caucho en hormigones para elementos de protección vial.

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Abstract. La problemática que se genera en la actualidad como consecuencia de la generación de desechos es de una complicación creciente en todo el mundo. En este marco existe uno en particular que es la acumulación totalmente descontrolada y desatendida de neumáticos inservibles y sus residuos.
El presente trabajo está orientado a la evaluación del desempeño de hormigones con la utilización de estos residuos como agregados alternativos en reemplazo de algunos tradicionalmente utilizados, buscando atenuar el impacto ambiental y social generado por los desechos mencionados.
Se moldearon probetas de hormigón realizadas con distintos porcentajes de reemplazo de agregados pétreos por caucho molido y se evaluó la influencia en las propiedades del hormigón modificado respecto del hormigón patrón, a los fines de estudiar la posible implementación de este material en la fabricación de elementos de protección vial.
Debido a que estos elementos pueden estar sometidos al impacto de vehículos, se comprobó que la incorporación de caucho modifica el módulo de elasticidad y se profundizó el estudio en ensayos de choque o que simulen un impacto.
A partir de los resultados obtenidos en laboratorio y su discusión se ha verificado que los hormigones con la incorporación de caucho mejoran su respuesta frente a un impacto respecto al patrón al absorber una mayor cantidad de energía.

Keywords: Hormigón, Caucho, Energía.

1 Introducción

El sostenido crecimiento anual del parque automotor, sin la existencia de una legislación que controle la disposición final de las cubiertas, plantea un escenario ambiental complejo. El Instituto Nacional de Tecnología Industrial (INTI), expuso que en Argentina la generación de neumáticos inservibles superaba las 100.000 toneladas anuales en el año 2010 [1]. Se puede estimar que dicha cifra alcanza las 130.000 toneladas en la actualidad. La disposición final de neumáticos inservibles descontrolada y fuera de cualquier criterio de reciclaje en cualquiera de sus formas, representa un grave peligro para la salud humana al convertirse en lugar de resguardo y fuente de reproducción de

insectos y animales transmisores de enfermedades graves y hasta letales para la población humana.

De igual manera, constituye un potencial riesgo de incendio incontrolable, que liberaría a la atmósfera grandes cantidades de gases y partículas nocivas para el medio ambiente y la salud de todos sus habitantes. Por otro lado, se estima que el tiempo de su descomposición natural o biodegradación supera los 600 años y, por su forma constructiva de aro, abarcan grandes extensiones de tierras aprovechables para otros usos más eficientes. Además, se genera una contaminación visual del entorno y comienza una incipiente, lenta y peligrosa degradación química de los neumáticos.

La industria de la construcción, al utilizar grandes volúmenes de recursos naturales, produce un impacto ambiental importante por lo que la cuantificación de ese impacto es fundamental para que sean posibles las acciones de mejoras. Este conocimiento permite analizar como los materiales pueden tener un mejor aprovechamiento de manera de causar menos perjuicios ambientales [2].

En ese mismo sentido, existen variadas posibilidades de reciclaje de los neumáticos inservibles, algunas son la reutilización, revalorización y recuperación energética. Hay múltiples ejemplos de ello y uno es la adición de partículas de caucho a hormigones, tema de estudio del presente trabajo. Su objetivo principal es analizar la influencia de la utilización de caucho de neumáticos inservibles molido en hormigones, como sustituto de los agregados inertes, en sus propiedades para su empleo en elementos de protección vial.

En una primera etapa, el trabajo consistió en el estudio de hormigones con distintos porcentajes de remplazo de agregados por caucho molido, realizando ensayos tanto en hormigón en estado fresco como en estado endurecido. Los resultados de este plan experimental permitieron definir las características más sobresalientes de cada mezcla.

Posteriormente, y a partir de la elección de la mezcla óptima, se realizaron sobre ésta los ensayos para evaluar su comportamiento frente a impactos y de allí se realizó teóricamente la deducción del comportamiento energético. Esto que permitió determinar las posibles ventajas de su utilización para la elaboración de elementos de la industria de la construcción, en especial de protección vial.

Se propone una opción atractiva técnica, económica y sustentable que es el uso de caucho reciclado para neumáticos en hormigones de cemento portland siempre que se usen porcentajes apropiados de caucho molido en tales mezclas.

2 Materiales

2.1 Ligantes

Para este trabajo se utilizó Cemento Portland con Filler Calcáreo CPF40, contemplado en la Norma IRAM 50000[3]. Para caracterizarlo se siguieron los procedimientos establecidos en las Normas IRAM 1623[4] e IRAM 1624[5], obteniéndose una densidad relativa de 2,99 y una superficie específica de 347 m^2/kg.

2.2 Agregados pétreos

Los agregados seleccionados fueron triturados pétreos provenientes de canteras de la provincia de Córdoba, Argentina, de tres tipos: Fino Hidrolavado (FH), Arena Gruesa (AG) y Binder. Se realizó el análisis granulométrico (Norma IRAM 1505 [6] y Norma IRAM 1627 [7]), determinación del porcentaje de material que pasa por el tamiz IRAM 75 µm (Norma IRAM 1540 [8] y determinación de la densidad relativa real, densidad relativa aparente y absorción de agua (Norma IRAM 1520 [9] o Norma IRAM 1533 [10]), cuyos resultados se indican en la Tabla 1 y en las Figuras 1,2 y 3.

Table 1. Caracterización agregados pétreos

Ensayo	FH	AG	Binder
Material fino que pasa por el tamiz 75µm [%]	2,60	1,10	-
Densidad Relativa	2,65	2,65	2,75
Absorción [%]	0,30	0,30	1,20
Tamaño máximo [mm]	0,30	2,36	9,50

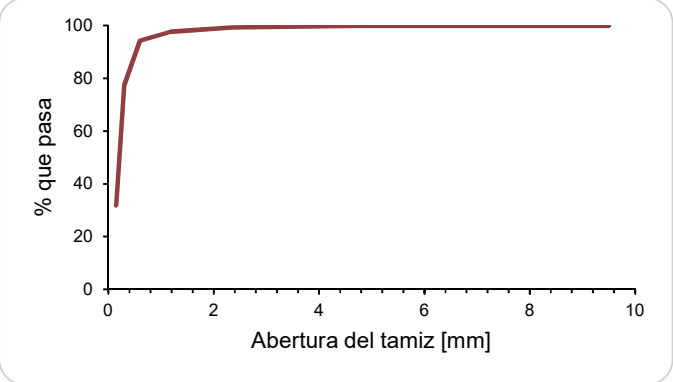

Fig. 1. Curva granulométrica FH

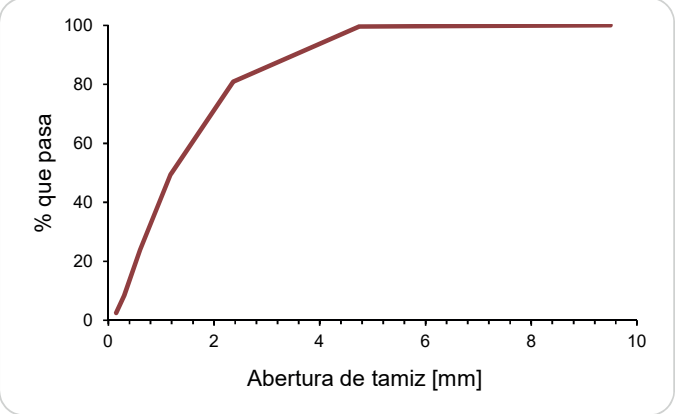

Fig. 2. Curva granulométrica AG

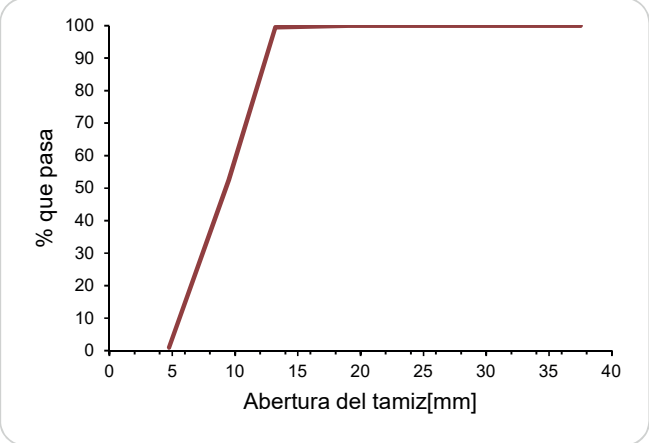

Fig. 3. Curva granulométrica Binder

2.3 Caucho Molido (CM)

Para el reemplazo de los agregados pétreos se utilizó caucho vulcanizado molido, proveniente de neumáticos inservibles, Figura 4, caracterizado por medio del análisis granulométrico (Norma IRAM 1505 [6] -Figura 5- y Norma IRAM 1627 [7]), determinación del porcentaje de material que pasa por el tamiz IRAM 75 µm (Norma IRAM 1540 [8]) y determinación de la densidad relativa real y densidad relativa aparente (Norma IRAM 1520 [9]) cuyos resultados se presentan en la Tabla 2.

Table 2. Caracterización CM

Ensayo	
Material fino que pasa por el tamiz 75µm [%]	0,10
Densidad Relativa	0,97
Tamaño máximo [mm]	2,36



Fig. 4. Caucho molido

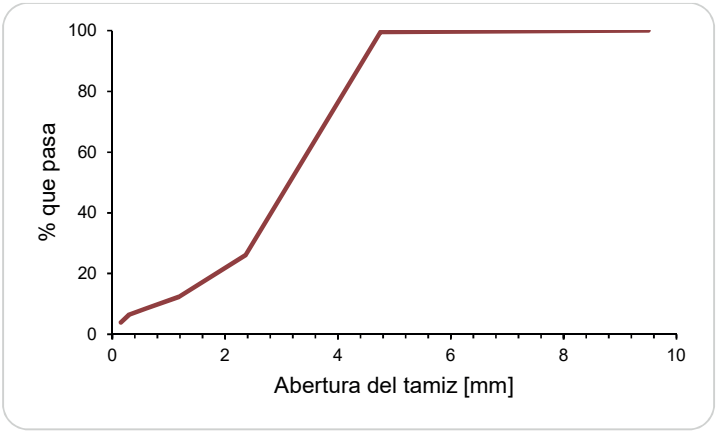

Fig. 5. Curva granulométrica del CM

3 Dosificaciones

El reemplazo de los agregados pétreos por caucho se realizó en volumen. Se proponen diferentes porcentajes de reemplazo del volumen total de agregados (0, 10, 17.5 y 30).

Las dosificaciones utilizadas se presentan en las Tablas 3 y 4, todas con una relación agua/cemento 0,40.

Table 3. Dosificación hormigón patrón.

Material	Densidad relativa	HFP: Volumen [dm^3]	HFP: Peso [kg]
Cemento CPF40	2,99	129	385
Agua	1,00	154	154
Caucho molido	0,97	-	-
Binder	2,75	340	936
AG	2,65	256	678
FH	2,62	121	317
Densidad teórica [kg/m^3]		2470	

Table 4. Dosificaciones hormigones con reemplazo de agregados.

Material	Densidad relativa	HF10: Volumen [dm^3]	HF10: Peso [kg]	HF17,5: Volumen [dm^3]	HF17,5: Peso [kg]	HF30: Volumen [dm^3]	HF30: Peso [kg]
Cemento CPF40	2,99	129	385	129	385	129	385
Agua	1,00	154	154	154	154	154	154
Caucho molido	0,97	72	69	125	122	215	208
Binder	2,75	340	935	340	934	337	926
AG	2,65	186	493	134	355	55	145
FH	2,62	119	314	118	309	110	285
Densidad teórica [kg/m^3]		2350		2259		2109	

4 Métodos de ensayo

En estado fresco se realizaron los ensayos de:

- Peso Unitario (IRAM 1562[11])
- Consistencia mediante el asentamiento en el cono (IRAM 1536[12])
- Exudación (IRAM 1604[13])

En estado endurecido se realizaron para todas las mezclas:

- Resistencia a compresión (IRAM 1546[14]) a 7, 14, 28 y 90 días
- Módulo de elasticidad (IRAM 1865[15]) a 28 días

- Absorción por inmersión (ASTM C 642 [16]) a 28 días

Luego de la realización de estos ensayos, se seleccionó la mezcla con las mejores condiciones según los resultados obtenidos y sobre sobre ésta se realizaron los ensayos de esclerometría (IRAM 1694[17])) en probetas de 15 por 30 cm y choque o impacto.

Para evaluar el comportamiento frente a choque, luego de analizar diferentes alternativas, se optó por adaptar un equipo ya disponible en el laboratorio, el equipo para la determinación del ensayo de choque en baldosas, según Norma IRAM 1522 "Baldosas aglomeradas con cemento con cara vista plana" [18]. Se moldearon placas de 20 por 20 cm de lado y 5 cm de espesor del hormigón patrón y del que contenía un 17.5 % de reemplazo de CM por agregado.

El método empleado es una adaptación de la Norma IRAM 1522; este ensayo permite determinar la capacidad de soportar impactos que puedan causar daños a la cara vista de las baldosas, tanto en sus aspectos estéticos como en su vida útil.

El ensayo consiste en dejar caer sobre la cara vista de la probeta la esfera de acero, desde una altura determinada e ir aumentando esta altura en (100 +- 5) mm hasta la rotura de la muestra, o si ésta no se produce, hasta alcanzar la altura máxima de 1000 mm. La altura de caída se determina entre plano definido por la cara vista de la baldosa y el centro de la bola de acero.

Cabe destacar que para este trabajo se modificó la masa, la dimensión y el sistema de sujeción de la esfera al soporte; la esfera que se utilizó para el ensayo tenía una masa de 2.295 gr y un diámetro de 59 mm.

La probeta se consideró rota cuando apareció una fisura que atravesaba la probeta de lado a lado.

En la Figura 5 se presenta el equipo modificado.



Fig. 6. Equipo de choque modificado.

5 Resultados

5.1 Ensayos en estado fresco

Los resultados de los ensayos realizados en estado fresco se encuentran resumidos en la Tabla 5.

Table 5. Ensayos en estado fresco

Ensayo		Unidades	HFP	HF10	HF17,5	HF30
Peso unitario	Peso unidad volumen	[kg/m3]	2460	2211	22156	1727
Trabajabilidad	Asentamiento	[cm]	3,0	2,1	2,1	2,1
Exudación	Volumen de agua exudada por unidad de superficie	[cm3/cm2]	0,02	0,04	0,04	0,07
	Porcentaje de exudación respecto volumen de agua de mezclado [%]	[%]	2,3	2,2	4,8	4,2

Las mezclas con incorporación de CM presentan menor peso unitario. Con respecto a la trabajabilidad, de acuerdo con el asentamiento del cono de Abrams, las mezclas con caucho presentan una pequeña disminución del asentamiento, sin embargo, ésta no fue significativa al momento del moldeado de las probetas, permitiendo una correcta colocación y compactación de la mezcla.

Los valores de volumen de agua exudada por unidad de superficie y porcentaje de exudación también varían respecto del patrón, pero se mantienen dentro de parámetros aceptables.

5.2 Ensayos en estado endurecido

Los resultados de estos ensayos se encuentran resumidos en la Tabla 6 y en la Figura 7 se presenta la evolución de la resistencia a compresión en función de la edad de ensayo.

Table 6. Resultados de ensayos en estado endurecido

Ensayo		Unidades	HFP	HF10	HF17,5	HF30
Resistencia a la compresión	7 días	[MPa]	21,80	6,80	8,30	1,60
	14 días		24,30	7,00	11,10	1,60
	28 días		26,30	7,60	10,50	1,90
	90 días		35,80	9,50	14,00	2,10

Módulo de elasticidad	-	[GPa]	33,80	14,60	12,40	3,70
Absorción por inmersión	Absorción después de inmersión y hervor	[%]	6,10	12,00	9,10	20,00
	Peso específico aparente	-	2,58	2,47	2,46	2,27
	Volumen de vacíos	[%]	13,70	22,90	18,20	31,90

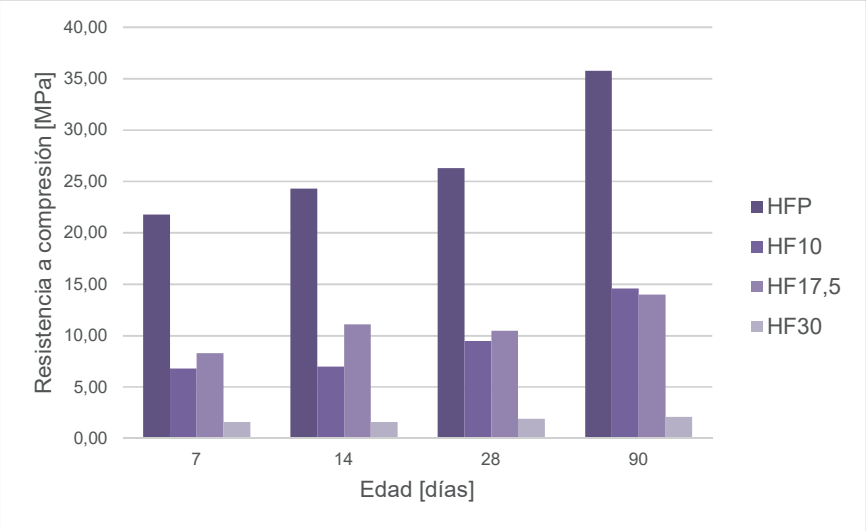

Fig. 7. Evolución de la resistencia a la compresión en función de la edad

De acuerdo con los resultados de resistencia a compresión, este material, que se podría calificar de ecoeficiente debido a que aprovecha un residuo industrial, no es apto para fines estructurales con los porcentajes de caucho incorporados ya que presenta una disminución significativa de la resistencia a la compresión, lo que imposibilita su uso en estructuras y/o elementos estructurales.

Coincidente con los resultados obtenidos en los ensayos de compresión axial, las mezclas con caucho molido presentan una mayor absorción lo que se traduce en un mayor porcentaje de vacíos.

El alto porcentaje de vacíos indica que la disminución de la resistencia mecánica es debida a la presencia de zonas débiles en la masa del compuesto, aunque también puede verse influida por una mala adherencia entre la pasta de cemento y los agregados de caucho molido.

De acuerdo con los resultados obtenidos en el ensayo del módulo de elasticidad con agregado de CM se obtienen valores menores a los de la mezcla patrón, lo que indica que para tensiones similares, los hormigones con agregado de CM presentarán mayores

deformaciones y esto puede traducirse en una mayor disipación de energía frente al impacto.

A partir de este último concepto, se evaluó el comportamiento al choque de la mezcla con un reemplazo del 17.5 % del agregado por CM al considerarse esta mezcla la más apropiada por su resistencia a la compresión y módulo de elasticidad. Los resultados de ambos ensayos, realizados a la edad de 28 días, se presentan en la Tabla 8.

Table 7. Resultados de ensayos de esclerometría y choque

Ensayo	Unidades	HFP	HF17.5
Choque	[cm]	57	60
Esclerometría	N°	31	31

En los resultados del ensayo de esclerometría no se encuentran diferencias significativas entre el hormigón patrón y el que contiene caucho, mostrando los resultados obtenidos, que el método no permite evaluar el comportamiento frente impactos.

Los resultados obtenidos en el ensayo de choque permiten observar que el hormigón con reemplazo de agregados por CM, soporta una mayor altura de caída antes de la fisuración. Con el objetivo de obtener una estimación de la mejora que representa este resultado, se utiliza la siguiente ecuación para calcular la energía absorbida por las piezas ensayadas:

$$E_i = \sum_{i=1}^{i=rotura} m_i * g * h_i = m * g * \sum_{i=1}^{i=rotura} h_i$$

Donde:

- E_i = Energía acumulada absorbida por la placa
- $m_{(i)}$= Masa del cuerpo que impacta (2295 gr)
- g = Aceleración de la gravedad (9,81 m/s^2)
- h_i = Alturas desde las cuales se produce la caída

Se tiene en cuenta una altura inicial de caída de 30 cm y una variación entre cada ensayo de 3 cm hasta llegar a la altura de rotura.

Se obtienen los resultados presentados en la Tabla 8.

Table 8. Energía acumulada absorbida por las placas de Hormigón.

	Unidades	HFP	HF17.5
Energía acumulada absorbida	[J]	97,94	111,44
Variación	[%]	-	+ 13,79

Si bien los valores obtenidos no son significativamente mayores, al considerar que el hormigón con CM tiene menor resistencia, este hecho indicaría una mejora en el comportamiento del hormigón que posee reemplazo de agregados inertes por caucho molido frente al choque.

6 Conclusiones

El material desarrollado, además de proponer un nuevo destino a los neumáticos inservibles, disminuyendo así sus impactos negativos, responde de la manera esperada en los aspectos evaluados.

Uno de los principales desafíos ambientales que enfrentan los municipios de todo el mundo es la eliminación de neumáticos fuera de uso. Para abordar este problema global, en este trabajo se ha avanzado en aplicaciones del caucho de neumáticos reciclado, para su aplicación en elementos de usos vial.

En estado fresco los resultados obtenidos del hormigón con CM han permitido lograr similar trabajabilidad y valores de exudación aceptables para los porcentajes de reemplazo propuestos.

En estado endurecido para el hormigón con CM se verifica una disminución de la resistencia a compresión, un aumento de la absorción de agua y una disminución del módulo de elasticidad.

La disminución que presenta la masa en hormigones con reemplazo de agregado por caucho molido, junto con la mayor capacidad de deformación, permitiría una reducción en los efectos negativos generados en los pasajeros de los vehículos ante un choque con un elemento fabricado con este material.

Según resultados obtenidos, tanto experimental como teóricamente, se verifica un comportamiento que permite mejorar la absorción de energía frente a impactos debido a su mayor capacidad de deformación respecto a la de hormigones convencionales.

Por este motivo podemos considerar al hormigón desarrollado como un material apto para la elaboración de elementos de protección vial, quedando abierta la determinación del valor óptimo de reemplazo de agregados inertes por CM de acuerdo con las características del elemento a diseñar.

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Increasing productivity of a beef production line using Lean 6 Sigma

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Abstract. Accelerated population growth and increased purchasing power lead to develop continuous improvements and new technological developments in the meat industry to meet the increasing demand for processed food worldwide. Although Lean Six Sigma has been widely used in manufacturing, its use in food processing is scarce, and the Chilean context is not an exception. The company under study recognized the need to transform itself and use continuous improvement tools such as Lean Six Sigma. This study was applied to the line of frozen meat patties in order to enhance product quality and standardize the production process, hence improving the operational excellence of the company in a business of global competitiveness. After analyzing the root causes for high variability and waste generation, solutions were produced, and countermeasures implemented at the production line. Main results include an increase in productivity of 18.8%, an 83% reduction of rework, an operating time reduction of 22%, and improvements in sigma levels for key variables.

Keywords: Lean Six Sigma, Processed food, Productivity, Efficiency, Quality.

1 Introduction

In the past decades, several efforts have been made to improve the quality of beef production driven by the increase in meat consumption trends; some elements influencing those patterns are changes in lifestyle, income, urban development, demography, food prices, improvement in meat processing, migration and the effect the mass media has on customers [1].

Beef attributes that add value to meat products are most appreciated by consumers willing to pay more for them. Buying some type of beef is strongly linked to its sensory properties; hence, consistent eating quality is one of the most important attributes [2]. Customers worldwide have preferences for extrinsic attributes such as price and certification, labels, brands, and information; and for intrinsic attributes like visible fat, meat color, and appearance [3].

Intrinsic attributes such as taste, tenderness and juiciness are highly valued, being tenderness the preferred one [4]. Such desirable sensory characteristics, such as juiciness and mouth feel of meat patties are associated with fat content [5] another important beef attribute; even though some consumers prefer lean meat, fat acts like a carrier for flavor compounds and contributes to the texture of the product. Reducing the fat content may alter product quality by causing the product to become firmer, rubberier, less juicy and darker in color [6], making muscle color a characteristic associated to fresh and palatable beef [7].

The choice behavior of the Chilean's consumer of bovine meat, analyzing factors such as price, origin, production method, and quality assurance [8] resulted in a purchase decision influenced by price, being it the least important for the majority of consumers, and the quality assurance attribute the most relevant. Other studies confirm color [9, 10], tenderness [10-12], juiciness [10], taste [12], freshness [9], price [12], and fat [9] as relevant attributes. Similar to international studies, sensorial attributes and low fat are highly desired by Chilean's consumers, being flavor [11] the key attribute justified for spending more in bovine meat for more than 2/3 of them [13]. Quality, as state by consumers, is relevant to deciding if a product is bought, and as such, it needs to be improved to remain in the competitive market.

In the following years, it is expected to have an increase in the demand for food worldwide, and meat consumption is not an exception. Beef burger patties are seldomly prepared from meat at home, but commonly purchased frozen from supermarkets or eaten at fast food restaurants, who are large consumers of Individual Quality Freezing beef patties. Emerging countries, which started with low meat consumption will eventually urbanize and change their lifestyles as their population and *per capita* income continuously grows. This could result in the population demanding more animal protein.

Southern Chile has a long tradition of beef production and related food processing industries. Its beef production increased in 2019 by 4.5% compared to previous year and about 10% of the production was exported. The export volume of beef has increased by 97.2% compared to 2018, being the main cause, China's demand, which increased by 161.2% in terms of volume; China represented in the year 2019, 77.6% of the total export value [14] for this industry. This growing trend indicates the importance of improving the productive system of bovine meat, in order to increase national and international competitiveness.

Productivity is an indicator widely used to assess business performance. The use of Quality Management techniques could help improving the production capacity and reduce waste by maintaining the attributes most valued by customers. Among those, Six Sigma, focused on reducing variation and defects, and Lean Manufacturing, focused on eliminating waste and increasing speed, aiming both to increase the quality, productivity, cost-effectiveness and competitiveness of companies.

Lean Six Sigma –LSS– combines approaches consisting of several tools and techniques. Six Sigma provides a way to measure the quality level to obtain 3.4 defects per million opportunities –DPMO– and identifies the number of opportunities within a process that could result in defects, so that possible causes of quality problems can be addressed and producing defects is avoided [15]; for many companies, this represents

a process for everyday continuous improvement to increase customer satisfaction [16]. Lean offers tools to reduce operating times and eliminate waste. Standardization has the goal of reducing the waste of products and increasing the productivity level, and as a consequence, the competitive position of the company in the market. Waste is produced mainly by returns, rework, second quality products, or customer attrition. Hence, some of the key benefits achieved by LSS implementation [17] such as cost saving, increased customer satisfaction, productivity improvement, higher quality and agility, and reduction in defects, were expected to be achieved in this case study application.

In the food industry, there is a lack of literature on how to implement Lean Six Sigma [18], representing only 2.1% for Agro/Food industries articles in a recent LSS literature review [19], and one article on a LSS implementation review [17]; some authors have researched on the practical implication of an LSS model in a food processing environment [20]. Previous studies on Six Sigma articles indicated that 63.3% were focused on manufacturing in contexts such as semiconductor, automotive, aerospace, chemical, software, pharmaceutical, steel, and aluminum industries [21]. Lean studies have focused on flow and speed up of processing by decreasing or eliminating waste in the seven forms of transport, inventory, motion, waiting, overproduction, over-processing and defects [17].

This work uses Lean Six Sigma applied through a DMAIC –Define, Measure, Analyze, Improve, Control– model to control the main variables of a frozen burger patty meat line, identified as critical for the production process. The contribution of this study for LLS in food processing is a suitable approach to improve quality and productivity, since performance enhancement and waste reduction continue to be critical subjects of such manufacturing companies.

2 Materials and methods

2.1 Materials

The case study was applied to a beef processing industry located in southern Chile. The company fulfills all national and international requirements regarding quality, food safety, hygiene, and health related to products manufactured for human consumption. The production line selected was the frozen burger patty line given the increasing number of kilograms being returned and the drop on monthly sales for that product. Data for the past three years was used to analyze the sales and defects behavior. For the preliminary analysis, data collected for nine months was used. After implementation of improvements, new data for three months was gathered, and results compared to prelim data. For each variable, authors followed the sampling size and random procedure already established by the company to collect data and statistically control the process. Media, standard deviation and variance measures were estimated for sample sizes.

2.2 Methods

This was the first LSS project in the company, so the approach used was a pilot deployment. In the pilot phase, specific problems are addressed to understand the methodology and to gain confidence on it [22]. Literature review was conducted on LSS implementation in the food industry with emphasis on meat processing.

To analyze the original process, the team meant to identify the main causes of process variation based on historical available data. Creating a learning environment for the team helped employees to understand the various phases of LSS; training them in the use of appropriate tools for each DMAIC phase [18] facilitated the implementation process.

Secondary data was obtained for a nine-month period using established procedures by the company for collecting information. Direct process observation provided in-depth knowledge to elaborate a SIPOC –Supplier, Input, Process, Output, Customer– diagram. The production process was documented through a flow diagram, and operating time was gathered to help constructing a Value Stream Map –VSM–. For each stage, different tools were applied. Data regarding sale volumes, returns, defects, rework, shrinkage and forfeiture were analyzed with trend graphics; a cause-effect diagram was elaborated after several brainstorming sessions to identify root cause.

Critical to Quality –CTQ– variables were identified through focus groups and interviews conducted with internal and external customers to define their needs regarding quality, service and price. All variables were analyzed in the company's laboratories through descriptive statistics in the form of histograms or pareto diagrams when needed. Control limits were estimated for critical variables of interest and compared to specifications; for those, defects were counted, and DPMO and process capacity indexes were calculated. The main wastes were classified and measured in percentages. Estimations of utilization, productivity and quality were calculated.

After implementation of countermeasures, new control and check sheets were designed to collect data for three additional months and to compare results. Hypothesis tests were conducted after implementation of changes to determine any statistical variation of media values and estimate new control limits if needed for critical variables.

2.3 Define

This phase was used to identify the process being studied, the CTQs, and the background of the problem. The SIPOC diagram and the VSM –not shown due to space limitations– required targeting time processes and identification of possible variation sources. A short version of the flow production process is shown in figure 1.

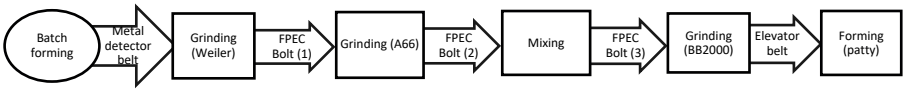

Fig. 1. Sub-process for burger patty line forming.

In order to understand sales behavior, data from the last 2 ½ years was analyzed. Table 1 shows monthly sales of the burger patty production line subprocess. As it can be observed, sales were decreasing. When this study initiated, sales of Year 3 represented 15% of sales from the same six-month period in Year 2.

Table 1. Yearly Sales (in kilograms)

Month	Year 1	Year 2	Year 3
1	62 230	124 876	18 900
2	17 150	62 314	0
3	17 150	105 679	31 500
4	19 040	83 466	15 750
5	135 900	174 992	15 750
6	137 327	84 808	15 750
7	96 264	104 540	
8	124 394	83 718	
9	121 150	4 213	
10	123 023	163 324	
11	119 620	123 916	
12	142 558	60 602	
Total	*1 115 807*	*1 226 446*	*97 650*

As well as sales were decreasing, returns were on the rise as presented in Table 2. Since no returns were registered for Year 3, data for Year 0 was used as reference. Converted to money, returns represent a cost of quality of 3.4% for Year 1 and 3.5% for Year 2 of the annual sales, respectively. Returns were related to quality problems, mainly out of customer's specification.

Table 2. Returns (in kilograms)

Month	Year 0	Year 1	Year 2
1			
2	14 939		17 975
3			1 295
4	189		
5	3 801		1 707
6		22 016	
7	25 071		
8			21 772
9		1 015	
10	2 855		760
11	626		
12	245	14 824	310
Total	*47 726*	*37 855*	*43 819*
% of Sales	*n/a*	*3.4%*	*3.5%*

In order to estimate the productivity of the sub-process line, production capacity – real versus theoretical – was observed for a nine-month period. The cost summary shown in Table 3 indicated 79% of cost was related to raw material, giving hints about the need to further analyze the mixing, grinding and forming stages of the frozen burger patty forming process shown previously in Figure 1.

Table 3. Cost distribution of burger patty line production

	Raw material	Operational	Distribution	Variable
Chilean pesos/Kg	2 175	484	63	42
Percentage	79	17	2	2

After analyzing the data, along with the SIPOC and VSM charts within the team, two-fold goals were defined: to standardize two main variables, temperature and fat percentage; and to increase the production process capacity by 5% in the mixing-grinding-forming line for a three-month period. To help achieve the objectives, a team of 10 people, including the general manager, was set up to address this problem. Since this was the first LSS approach taken by the company, the team leader and manager of continuous improvement and control, trained the team members in basic principles of LSS before continuing with the following phases. Meetings were set up to be held every other week, and each team member was assigned a role, responsibilities and resources.

To define internal customer's needs, specifications were reviewed, and meetings were held. It helped identify requirements for: temperature at the Forming patty machine, average fat percentage, and the absence of foreign elements in the raw material. Through brief interviews with main external customers, their needs were collected and specifications re-defined, as shown in Table 4.

Table 4. Burger patty specification's variables to be controlled

Weight (gr)	Thickness (mm)	Diameter (mm)	Cooking T °Celsius	Sensorial assessment
112.5–115.3	11.2–12.6	115–123	69–74	>85%

2.4 **Measure**

Historical data was collected for each one of the different stages of the subprocess regarding: ticket control, temperature control by batch, defects by variables of interest, machine preventive and corrective maintenance, belt functioning, equipment life control sheet, tools control sheet, shift times, statistical process control charts for selected variables, sensorial evaluation, and meat condition. This was consistent with factors identified by several authors to use LSS, such as process variation, waste elimination, competitiveness increase, cost decrease, inventory reduction, and process efficiency

improvement. In the food industry, product weight and size variability are commonly associated with process variation [20, 23].

Data gathered was used to construct histograms for each variable to be studied and to calculate the DPMO and sigma level for fat percentage and variables affected by fat variation, such as weight, thickness and diameter, as shown on Table 5. The burger patty size chosen, named AMD, represents the majority of the sales. Fat percentage of raw material in the batch was obtained through analysis on the *Food Scan* equipment located in the company's lab.

Table 5. Critical to Quality "As Is", Burger patty size 114 gr –AMD–

	Fat %	Weight	Thickness	Diameter
Spec. limits	22.0 –24.0	112.50–115.30	11.2–12.6	115–123
Sample size	182	482	1 928	410
Opp./batch	27	11	11	8
DPMO	20 960	31 686	46 444	62 500
Sigma level	3.55	3.38	3.14	3.03
Performance	97.9%	96.83%	95.36%	93.75%

As an example of descriptive statistics used by the team, a histogram for the diameter's variable is presented in Figure 2, where control limits were calculated and compared with specifications. All diagrams constructed for other variables are not shown due to lack of space. As it can be seen for this variable, the process is able to comply with specifications –wider curve– and variation is lower than expected, although the process is slightly uncentered, as confirmed by its Cpk value.

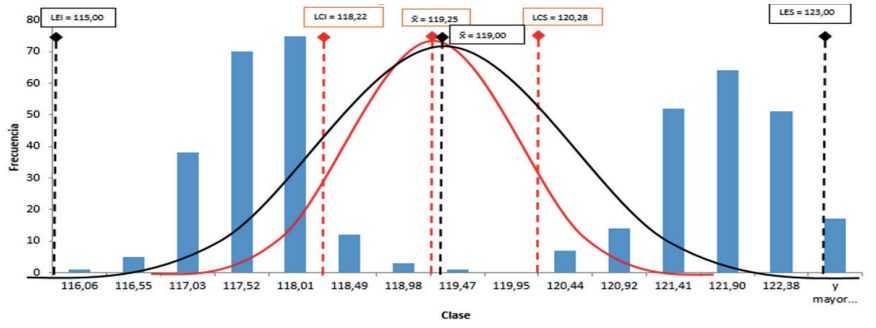

Fig. 2. Histogram for diameter of burger patty.

Later on, three additional quality attributes were studied: cooking temperature, storage temperature, and the absence of unwanted elements in raw material. Histograms were drawn for each case and control limits compared to specifications. For cooking temperature, only 0.2% of burger patty samples were found to be out of specifications, meaning a sigma level of 5.6. Thus, it was not further investigated.

Regarding storage temperature, data was collected from months 7 through 9. The temperature varied according to the fat percentage in the mix. A histogram was elaborated, and data compared to specifications, showing excessive variation for frozen raw material; the average was -8.5°C while the media specification indicates -4.5°C. Temperature is relevant to forming the patty burgers, thus it needed to be addressed.

A sensorial assessment [24] named Cutting was performed of Batch AMD 157540, in the first month of this study, obtaining a sensorial approval of 89.2% –85% was the minimum expected value–. Since some variables measured by this analysis –flavor, tastiness, texture defects, juiciness, tenderness, unscrambling, appearance, seal conformance– are intrinsic and relevant to customers; this evaluation had to be repeated after implementing changes.

No foreign material was found in the process line; thus, it was not further addressed by this study.

Average production times for all stages of the subprocess shown on Figure 1 were estimated, adding to an average of 02:28:58 hours per batch.

Regarding waste, Table 6 shows data for a nine-month period of study. Waste mainly occurs at the Forming stage of the subprocess. From the data it was clear that waste should be reduced to increase productivity.

Table 6. Waste in kilograms for burger patty forming line.

Month	Production	Forfeiture	Rework	Shrinkage
1	406 754	1 629	4 304	10 060
2	435 552	1 630	3 778	6 945
3	455 137	1 303	2 761	7 403
4	324 020	1 474	2 849	7 193
5	289 127	1 716	3 633	6 687
6	308 260	1 673	4 971	7 356
7	405 203	1 562	5 154	7 936
8	446 043	1 527	4 821	10 248
9	292 349	1 210	4 416	4 772
Total	**3 362 443**	**13 724**	**36 686**	**68 600**
Average %		0.4%	1.1%	2.0%
Chilean pesos*		**41 460 808**	**30 999 890**	**207 240 521**

**Estimated value / 1 USD = 665 Chilean pesos in year of study*

The estimated quality loss for a nine-month period was valued at 420 603 USD due to shrinkage, rework, and forfeiture. This data was a key element to promote improvements to reduce waste and was consistent with literature, which considers cost, defects, value and time to be drivers for implementing LSS in the food industry [18].

2.5 **Analyze**

A data collection sheet was designed to gather all desired information: batch number, production date, code, temperature, fat percentage, weight, diameter, and thickness. A cause-effect diagram was elaborated. From it, main causes of possible variability on the final product were detected for machines –Weiler, A66, Mixer, Conveyor belt, and Forming–, people –training–, methods –unknown, outdated–, materials –inventory conditions–. Details for each machine were documented, discussed with the team members, and solutions proposed. Several options were analyzed to reduce the variability of the fat percentage in the product, regarding formulation adjustments and new methods to form the batch. Operational time was analyzed as well as the type of mold being used to form the patty burger.

The bottleneck of the subprocess is the Forming Stage, composed of Machine F16 and F19. They have a design capacity of 2 160 kg/hr. and 972 kg/hr.; shift times of 11.5 hours and 9.5 hours 5 days per week; and number of people per shift of 12 and 3, respectively. Combined, Forming has a design capacity of 3 132 kg/hr. and a planned production time, also known as maximum rated capacity of 95% the design capacity, equals to 2 975.4 kg/hr. The output rate is calculated dividing the production volume by the run time. Finally, productivity is estimated by multiplying utilization and efficiency. Calculations are shown in Table 7.

Table 7. Frozen burger patty production line (nine months)

Production volume	Available run time	Run time	Utilization	Efficiency	Productivity
3 362 443 kg	1 723	1 424	82.3%	79.3%	65.2%

Regarding the Overall Equipment Effectiveness –OEE–, which includes quality loss to estimate the fully productive time, it can be calculated as,

$$OEE = \%Performance \times \%Availability \times \%Quality \quad (1)$$

Performance is the speed at which the machine or workstation runs expressed as a percentage of the speed it is designed to run. It is synonymous of efficiency. Availability is the asset operating time expressed as a percentage of available operating time. Quality is the total number of good units produced expressed as a percentage of the total number of units that were started.

The theoretical time needed to produce 3 362 443 kilograms was 1 130 hours –performance time–. Performance is equal to 79.3% and availability is equal to 82.3%, same as utilization. Of the 3 362 443 kilograms produced, only 96.5% were of good enough quality. The other units had to be reworked, before sale or scrapped. This means the good kilograms expressed as time is 1 090 hours, and the quality is 95.1%. Hence, OEE_{before} equals to 62.1%.

This calculation shows that the total losses during the day for this machine were 37.9% of production time. Eventually, this represents a large amount of time loss, decreasing the profits if the productivity of the Forming stage was higher. Therefore, it

was important to identify the main root causes of this loss and to implement the necessary actions to reduce or eliminate waste.

2.6 **Implement-Improve**

New working procedures were standardized, documented, and implemented. Employees received training; possible causes of failures were identified and addressed properly for each stage of the subprocess. Measures were taken to reduce process time. Raw material temperature handling and storage were strictly controlled.

In order to stabilize the fat percentage, the ingredients and formulation were prepared the day before production; this new method allowed to have adequate quantities and to load the fat raw material in alternative ways into the batch. This change reduced the deviation for fat percentage from the media to 0.4%, and the DPMO from 20 960 to 137, improving the sigma level from 3.55 to 5.14 as presented on Table 8.

Regarding weight, thickness and diameter of burger patties, analyses performed previously showed a close relationship between weight and the mixing time. The type of mold used in the Forming Stage affected all three variables. New molds were bought, a mold matrix was constructed with diameters and codes for the size and type of each burger patty used in the machines.

After implementing the changes, new samples were taken and statistics compared to the previous data; from those, DPMO for weight was reduced from 31 686 to 16 142 and the sigma level was improved by 5.5%. Data taken for comparing thickness shows an reduction in DPMO from 46 444 to 22 727; however, such number is still high and more efforts need to be done; its sigma level was increased from 3.14 to 3.37. The other CTQ, diameter, had a significant improvement: from 45 454 DPMO to 3 504 for the new sample taken. This represents an improvement in the sigma level from 3.14 to 4.25. All results are presented on Table 8.

Even though all four CTQs were improved, the process was still not centered in regard to specifications; yet three variables had $Cp < 1$ and $Cpk < 1$, except for diameter, indicating room for improvement on those variables.

Table 8. Critical to Quality "After Implementation"

	Fat %	Weight	Thickness	Diameter
Spec. limits	22.0 – 24.0	112.50–115.30	11.2–12.6	115–123
Sample size	270	107	428	214
Opportunities/batch	27	11	11	8
DPMO	137	16 142	22 727	3 504
Sigma level	5.14	3.56	3.38	4.25
Performance	99.99%	98.39%	97.73%	99.65%

Burger patty quality. As discussed earlier, cooking time does affect the quality of the product. Data analysis showed that the operational cooking time was not complying

with specifications, being skewed to the left. After studying the process, a new procedure was written and implemented.

Later on, as changes were implemented a new sensorial evaluation –Cutting– was performed. The panel responses evaluating the burgers on batch AMD 160348 gave them a 91.3% acceptance, an increase of 2.1 % in quality perception from the previous evaluation.

In order to stabilize the temperature of raw material in cooler rooms at -5°C, several tests were performed with the goal of reducing mixing times and achieving the optimal temperature needed by the burger patty maker. Figure 3 shows the values registered. Frozen raw material should have an average temperature of -4.5°C. Table 9 shows the summary of the results. For fresh products, 1.0°C was the minimum average temperature expected. From the figure and the results, it can be seen temperature was set under control with the measures taken.

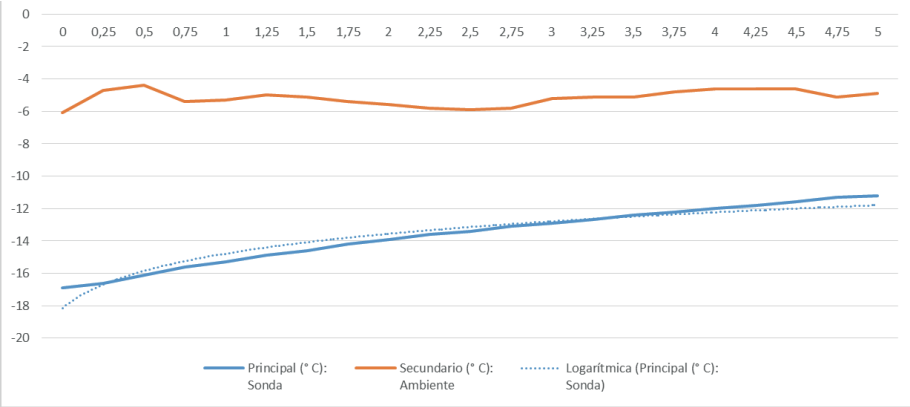

Fig. 3. Tempering curve for raw material

Table 9. Average raw material temperatures °C

Raw material	Meat block 1	Meat block 2	Meat block 3	Meat block 4
A85SGP fresh	2.0	1.9	2.0	1.7
A90SCB frozen	-3.6	-4.0	-4.7	-5.6
B50SCB frozen	-3.3	-3.6	-4.2	-5.1
M30ECB frozen	-5.6	-5.3	-5.7	-5.1
2M70CB frozen	-4.4	-5.5	-5.0	-4.2

Processing time. As shown in Table 10, operating times were reduced by reprogramming the production line, applying changes to the temperature of the raw material storage, regulating the fat percentage addition to the mix, and controlling better the block meat temperatures. Time estimations were supported by the VSM chart elements. All

changes were documented and standardized in written procedures. Total processing time was reduced by 22.7%.

Table 10. Average patty burger line operating time

Steps	Before	After
Batch forming	0:04:20	0:03:30
FPEC1	0:05:05	0:04:40
FPEC2	0:06:29	0:06:50
Loading mixer	0:08:32	0:07:29
Unloading mixer	0:14:02	0:14:10
Loading FPEC3	0:24:30	0:18:00
Loading BB2000	0:39:00	0:28:00
F16 /719	0:47:00	0:34:00
Total time	***2:28:58***	***1:56:39***

Waste reduction. Regarding waste in the form of forfeiture, rework and shrinkage occurred in the Forming line, after improvement new data was collected. A comparison is shown in Table 11, with reduction in the types of waste targeted by the changes implemented: rework and shrinkage. Rework was reduced by 83% and shrinkage by 25%. Estimated monthly quality loss due to rework and shrinkage was estimated at 46 733 USD. After implementation, this loss was reduced to an average of 12 020 USD per month, and 75% reduction.

Table 11. Waste Before (January-September) and After (October-December)

	Production	Forfeiture	Rework	Shrinkage
Before	**3 362 443**	**13 724**	**36 686**	**68 600**
		0.4%	1.1%	2.0%
After	**397 840**	**1 881**	**2 390**	**7 278**
		0.4%	0.6%	1.8%

Productivity improvement. Instead of running both machines at the same time, Forming equipment F19 and F16 were programmed to work at different periods of time. The results from data taken after changes were implemented, indicate an improvement in efficiency and productivity. Data for the last three months had an average daily combined production of 21 610 kilograms, with an effective capacity of 2 975 kg/hr. and a real capacity of 2 507.6 kgs/hr. Most of the production was processed on the Forming machine F16, leaving F19 for small batches. New results compared to data from Table 7 show that efficiency was improved from 79.3% to 97%, utilization increased from 82.3% to 86.7%, and productivity from 65.2% to 84%.

Of the 21 610 average kilograms produced daily, only 97.2% were of good enough quality. The other units had to be reworked before sale or scrapped. Hence, OEE_{after} was estimated to be 81.7%. Compared to 62.1% from the previous nine months, there was an increase of almost 19.6% in OEE for the processing line.

2.7 **Act**

Data taken at the beginning of the process showed a utilization of 92.8%, efficiency of 55.2% and productivity of 51%. Since machine F19 was being underutilized, it was discontinued. By using only F16, labor force was reduced by 17%.

In order to verify the changes for the media of the variables, a hypothesis test was performed for each one. Results are shown on table 12. Each hypothesis test was associated with a probability and a type-I error rate of 5%, under the assumption that the variables had a Normal distribution, with unknown mean μ, and known standard deviation σ; random samples were obtained, and sample means and Z_0 values were calculated.

Table 12. Hypothesis test for media with known sigma value

	Fat %	Weight	Thickness	Diameter
	21.45	111.44	11.16	119.25
σ	0.33	0.5	0.23	1.16
n	27	107	428	214
$\bar{x}$	23.8	113.93	11.25	119.25
Z_0	-23.9	-46.6	-7.2	0
Decision	Reject	Reject	Reject	No reject

Since the media changed for three variables, new control limits were calculated for those. Given the fact that variation remained high for some variables, further improvements is needed. Those efforts were beyond the scope of this work. To maintain the changes, strict procedures were implemented to control the critical CTQs and keep waste level and processing times at the new rates. Those aspects in no need of change, such as absence of foreign material, were kept being monitored. Temperature needed in storage of raw material was controlled by regular preventive maintenance of equipment.

3 Conclusions

This study had a two-fold objective: to standardize two main variables, temperature and fat percentage; and to increase the production process capacity by 5% in mixing-grinding-forming for a 3 month-period. Through the study, it was necessary to analyze variables, such as weight, diameter and thickness of the burger patty, all affected by the percentage of fat and the temperature it was kept in the storage room. Several Lean and Six Sigma tools were utilized while implementing the DMAIC model. With the solutions provided by the team, fat percentage was stabilized and DPMOS were reduced for weight, thickness and diameter of burger patties, gaining improvements at the sigma level of 5.5%, 7.5% and 35%. However, the process is still not centered in regard to specifications, indicating room for improvement on those variables. Overall line efficiency was improved from 79.3% to 97%, utilization increased from 82.3% to 86.7%, and productivity from 65.2% to 84%. Those results are well above the goal of 5% increase. Production time per batch was reduced from 2:28:58 to 1:56:39 hours, representing a 22% improvement. OEE for the line increased from 62.1% to 81.7%. Sensorial assessment, which measures the quality perception of customers was increased by 2.1 % for burgers patties; this was achieved as storage temperature allowed fat percentage to stabilize. Rework was reduced by 83% and shrinkage by 25%, representing estimated annual savings of 416 448 USD. New procedures were settled to ensure changes are kept in time.

Future research includes identification of non value-added activities and 5S implementation. The application of LSS in the processing food industry is scarce, being this work, to the best of the author's knowledge, the first of its kind in the Chilean context of beef food processing.

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COVID-19 Pandemic Effects on the Idiosyncratic Risk of the Brazilian and Emerging Markets

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Abstract. The Covid-19 Pandemic affects social and economic relations in all national economies and the world economy, and their financial markets. Investment and production financing in economies take place through these markets, in particular in the capital market. The idiosyncratic risk represents the risk associated only with a specific productive project, with an economic sector, or with a specific national economy. This work aims to estimate the idiosyncratic risk of the Brazilian economy, through heteroscedastic conditional models, to verify the initial impact of the Covid-19 Pandemic on the risk associated with productive projects developed in the Brazilian and emerging economies, and to their financing and investments. Daily data in US$ covering the period from June 30, 2017 to July 1, 2020 were used.

Keywords: Covid-19 Pandemic, Idiosyncratic Risk, Brazilian Economy.

1 Introduction

The sanitary crisis caused by the Covid-19 Pandemic is compared to the 1918 crisis caused by the H1N1 Influenza Pandemic. The sanitary crisis that triggered the Covid-19 Pandemic began with news of a public health problem that started in Wuhan, capital of Hubei province in China, caused by a virus identified as SARS-CoV-2, a new Coronavirus, which quickly spread over 180 countries causing high mortality. Compared to the 1918 crisis caused by the H1N1 Influenza Pandemic that haunted the humanity in the beginning of the twentieth century, Covid-19 Pandemic has also triggered many studies and research in the most diverse areas of knowledge.

The great crises repercussions which spread throughout the world during the last centuries have been the object of studies and researches over time. Most of these researches were aimed to verify the immediate effects and the influence of these crises on the world population welfare and the economic and social behavior and relations in the world. Among these researches, [1] can be mentioned. In a broad study on the economic impacts of the Influenza Pandemic, [1] highlights that the loss is more human than material. The economic impacts of this Pandemic, according to [1], can be classified as direct and indirect. The study includes hospital costs, lost days of work, medicine costs, the decrease in tax revenue and the increase in health and economic aid expenditures to sectors in difficulty, followed by government fiscal deficits as direct

impacts. Among the indirect economic impacts [1] includes the economic multiplier effects of direct costs and the behavior of consumers, affecting consumption relationships.

The crisis caused by the Covid-19 Pandemic had a direct impact on social and economic relations in all regions of the world affecting national economies and the world economy as well as world financial markets. These financial markets signal the expectations of national economies and the world economy, through money, foreign exchange, credit and capital markets. While in the public health area, efforts are being made to minimize the serious problems in public health systems, economic agents seeks to verify the problems that the Covid-19 Pandemic has caused and should cause in the years to come, with the growing disorder in the costs and the production chains.

The financing and investment of production in economies happen, generally, through the financial market, in particular via the capital market. The productive projects that provide the necessary infrastructure for the development of economies and maintenance of jobs and the income growth have in the capital market the source of resources for investments and financing. In this way, one of the important advanced indicators of the economy is the performance of the capital market, whose first indicator is the stock market profitability index. This index reflects the expectations of economic agents regarding the economy, and allows estimates of the volatility or risk associated with productive projects, sectors of national economies, a national economy and the global economy. The volatility or the total risk has two components, the market risk and the idiosyncratic or unique risk. The market risk refers to the risk of exposure of productive projects, sectors of national economies, and a national economy, to the behavior of the respective market portfolios, respectively, the sector project portfolio associated to the productive project concerned, the portfolio that represents the national economy, and the portfolio that represents everything that is produced in all national economies. The idiosyncratic risk is the unique risk associated only with a specific productive project, or the project portfolio of a sector, or of a sector of a national economy, or of a national economy. Thus, each national economy has as an indicator that represents the portfolio that encompasses most of the productive projects of each of the national economies, that is, the indicator closest to a market portfolio which is the equity market profitability index of each national economy. These economies are part of the world economy, which has a profitability index of the global stock market as a proxy for the market portfolio. Some agencies or market institutions calculate and make available some profitability indexes of the nationals and global stock markets.

Many studies and researches started with the objective of verifying and mitigating the pressing public health and economic problems that present themselves during the Covid-19 Pandemic and the possible problems that will be originated. Among these studies it must be mentioned: [2], which deals with idiosyncratic and systematic shocks caused by pandemics in financial markets; [3], who discusses the economic impact of the Covid-19 Pandemic; the study by [4], which deals with the influence of the Covid-19 Pandemic on the global economy through the capital market using the global market share profitability index to study the long term relationship between the markets of actions and the effects of the Covid-19 Pandemic; the research by [5], which deals with the influence of the Covid-19 Pandemic in the capital markets of selected countries; the

work by [6], which presents a study on the effect of the lockdown period on the Indian capital market through a sample of 31 companies listed on the Bombay Stock Exchange; and other researches related to this topic, such as [7], [8], [9], [10], [11] and [12].

With regards to the risk, based on the seminal work of [13], many researches have been carried out seeking, in an appropriate way, to determine the total risk and its components: systematic risk and idiosyncratic risk. The estimation of the market model, or the Single Index Model, suggested by [13] allows the determination of the main indicator of market risk, the beta coefficient, and the idiosyncratic risk, also called specific risk or unique risk. In a pioneering work [14] seek to forecast the systematic risk and the specific risk of stocks and propose stochastic models for deter-mining the beta coefficient and the idiosyncratic risk using the Single Index Model. From this work, many researches were developed. [15] estimated the idiosyncratic risk and its relationship with the monthly stock returns using the three-factor model, suggested by [16]. Besides that [15] employed some of the ARCH family for volatility models derived from the Autoregressive Conditional Heteroscedasticity Models available in the finance literature developed from the seminal work of [17] and the work of [18]. In another relevant work [19] note that the idiosyncratic risk has been neglected to the detriment of a greater emphasis given to the systematic or market risk in determining the risk premium. In turn, [20] emphasized the importance of assessing specific or idiosyncratic risk. In general, market volatility increases in the periods leading up to these crises and during crises periods, as observed by [21] in the recent period of the world economy with the subprime crisis. Among the most recent studies that attempt to estimate idiosyncratic risk, we can mention [22], which deals with this risk as an anomaly, [23], with data from the Japanese economy, and [24], that verify the idiosyncratic risk of the Chinese stock market.

This work aims to estimate the idiosyncratic risk or unique risk of the Brazilian economy and the emerging economies, using heteroscedastic conditional models of the ARCH family models in order to verify the impact of the Covid-19 Pandemic on the risk associated with productive projects developed in the Brazilian economy and the other emerging countries as well as on the risk associated with investments and financing.

Besides this introduction in Section 2 the methodological approach implemented in the research is presented. Section 3 presents the data or the sample used. The analysis of the results obtained in this research are reported in Section 4. Finally, Section 5 presents the conclusions and final comments of this work followed by the bibliographic references used.

2 Methodological Approach

In the development of this work, models were estimated according to the classical statistical inference procedures, which are described in econometrics and time series handbooks such as [25], [26], [27], among others.

The concept and the determination of the total risk and its portions, systematic risk and idiosyncratic risk, were established from the Single Index Model, or the market model proposed by [13], which explain the risk asset portfolio returns through the returns of market portfolio. In the scope of this work, the risk asset portfolio is characterized by the Brazilian stock market profitability index represented by the MSCI Brazil index while the emerging stock market profitability index was represented by the MSCI Emerging index and the world stock market portfolio is characterized by the global equity market profitability index, represented by the MSCI ACWorld index. These indices are calculated by Morgan Stanley Financial Services (MSCI) and will be described in this work in the section dealing with the data used. The market model can be described as follows:

$$R_t = \alpha + \beta R_{Mt} + e_t \tag{1}$$

Where: R_t = the return of MSCI-Brazil index or MSCI-Emerging index in period t; R_{Mt} = the return of ACWorld index in period t. Thus, the conditional average and conditional variance of the financial asset returns can be determined as follows:

$$\textit{Mean}: \quad E(R_t|R_{Mt}) = \alpha + \beta R_{Mt} \tag{2}$$

$$\textit{Variance}: \quad V(R_t|R_{Mt}) = \beta^2 V(R_{Mt}) + V(e_t) \tag{3}$$

The estimation of the beta coefficient, the main indicator of market risk, takes place through linear regression models, as for example in the works elaborated by [28], using corrections from a classic univariate model, and by [29], using a multivariate Bayesian model. The estimation of the idiosyncratic risk time series can be done through volatility models such as the ARCH family models, in particular, the GARCH model proposed by [18]. The GARCH model seeks to capture a common behavior in financial asset return time series, in which high values are also followed by high values in the following periods, not necessarily in the same direction, following a predictable process. Therefore, a market model that allows obtaining estimates of the two components of the total risk can be built. Additionally to the GARCH model, some of the main models of the ARCH family were tested, such as ARCH, IGARCH, EGARCH and TGARCH, as described in [25]. Using the model selection criterion suggested by Akaike, the AIC, which can be seen in detail in [26] or [27], the market model to estimate the idiosyncratic risk was selected. With the alpha and betas parameters greater than zero, the volatility models estimated in this work have their general form given by the expressions shown below: the ARCH (q) model represented by the expression (4); the GARCH (p, q) model represented by expression (5); the IGARCH (p, q) model represented by expression (6); the EGARCH (p, q, r) model represented by the expression (7); and TGARCH (p, q, r) model represented by the expression (8).

$$\sigma_t^2 = \alpha_0 + \sum_{j=1}^{q} \alpha_j e_{t-j}^2 \quad (4)$$

$$\sigma_t^2 = \alpha_0 + \sum_{i=1}^{q} \alpha_i e_{t-i}^2 + \sum_{j=1}^{p} \beta_j \sigma_{t-j}^2 \quad (5)$$

$$\sigma_t^2 = \sum_{i=1}^{q} \alpha_i e_{t-i}^2 + \sum_{j=1}^{p} \beta_j \sigma_{t-j}^2 \quad (6)$$

$$ln\sigma_t^2 = \alpha_0 + \sum_{j=1}^{p} \beta_j ln\sigma_{t-j}^2 + \sum_{i=1}^{q} \alpha_i \left| \frac{e_{t-i}}{\sigma_{t-i}} - E\left(\frac{e_{t-i}}{\sigma_{t-i}}\right) \right| + \sum_{k=1}^{r} \gamma_k \frac{e_{t-i}}{\sigma_{t-i}} \quad (7)$$

$$\sigma_t^2 = \alpha_0 + \sum_{i=1}^{q} \alpha_i e_{t-i}^2 + \sum_{j=1}^{p} \beta_j \sigma_{t-j}^2 + \sum_{k=1}^{r} \gamma_k d_{(e_{t-k} \leq 0)} |e_{t-k}|^2 \quad (8)$$

Thus, the model used in this work to estimate idiosyncratic risk was a heteroscedastic linear regression model, where the stochastic terms are distributed according to a Student's t distribution and the variance given by a GARCH (1, 1) model which can be described as follows:

$$R_t = \alpha + \beta R_{Mt} + e_t \ , \ e_t \sim Student\ (0; \sigma_t^2; \nu) \quad (9)$$

$$\sigma_t^2 = \alpha_0 + \alpha e_{t-1}^2 + \beta \sigma_{t-1}^2 \quad (10)$$

3 Data Used

The primary data referring to the stock market indices that form the sample used in this work were collected on the Investing.com website. These indices are calculated and released by the financial services company Morgan Stanley Capital International (MSCI). These indicators were: the profitability index of the Brazilian stock market - MSCI Brazil; the profitability index of the stock market of emerging countries - MSCI Emerging Markets; and the worldwide stock market profitability index - MSCI All-Country World Equity - or simply the MSCI ACWI Index. The Brazilian stock market index is made up of 56 shares and represents 85% of the equities traded in the country and includes the main sectors of the Brazilian economy and is detailed at https://www.msci.com/search?keywords=brazil. The emerging markets index is composed of equities traded in China (33.00%), South Korea (13.02%), Taiwan (11.35%), India (9.16%), Brazil (7, 73%), South Africa (5.89%), Russia (3.77%), Mexico (2.55%), Thailand (2.34%) and others (11.59%). Further details on the composition of the emerging countries stock markets indicator are at https://www.msci.com/search?keywords=Emerging+Markets. And the global stock market index used is composed of equities from 11 sectors of the economy traded on the markets: from developed countries in the Americas, 2 countries, from Europe and the Middle East, 16 countries, and from the Pacific, 5 countries; and from emerging countries in the Americas, 6 countries, Africa, Europe and the Middle East, 11 countries, and Asia, 9 countries. Further details about the description of this index can be seen https://www.msci.com/acwi. All

information collected was daily data in US$, covering the period from June 30, 2017 to July 1, 2020.

Table 1, below, presents the time series statistical summary of interest to obtain this research results, that is, an estimate of the idiosyncratic risk time series using the market model. It can be seen that the time series location measures are disparate and do not have a symmetry. With regard to the volatility of the return time series it is high, as expected from market price returns or variations. As for the asymmetry and kurtosis coefficients: it can be seen that all the asymmetry coefficients shown in Table 1 differ from the asymmetry coefficient of a normal probability distribution, the same happens with regard to the kurtosis coefficients calculated for all series used. The Jarque-Bera test confirms the inferences made from observing the coefficients of asymmetry and kurtosis, that is, for every of the time series used, the normality hypothesis cannot be accepted. With regard to the stationarity hypothesis of the time series summarized in Table 1, the stationarity possibility of the time series of the quotes of the MSCI-ACWorld index according to the results of the ADF test cannot be rejected. However it should be noted that the extensions to the ADF test do not allow acceptance of the stationary hypothesis of the quotes of the global stock index MSCI-ACWorld.

Regarding the time series of the quotes of the MSCI-Brazil index, the hypothesis of stationarity for the ADF test and its variations cannot be accepted. Regards the MSCI-Emerging markets index, although stationarity is not rejected at the level of significance of 8%, for the ADF test the alternatives of the ADF test, without the constant or the trend component of the series, point to a contrary decision , that is, the stationarity hypothesis of the index corresponding to the portfolio of equities traded in emerging countries is not accepted.

Table 1: Statistical Summary of Time Series

Statistics	Quotes MSCI ACWorld	Quotes MSCI Brazil	Quotes MSCI Emerging	Return MSCI ACWorld	Return MSCI Brazil	Return MSCI Emerging
Mean	508.4525	1974.8900	1055.6170	0.0002	-0.0002	-0.0001
Median	510.7950	2051.7250	1054.8600	0.0007	0.0006	0.0006
Maximum	581.0200	2428.7100	1273.0700	0.0806	0.1516	0.0557
Minimum	384.0400	1036.3000	758.2000	-0.1000	-0.1943	-0.0694
Std Deviation	29.0043	299.2842	83.3356	0.0111	0.0238	0.0107
Skewness	-0.2542	-1.2263	-0.2568	-1.7250	-1.4790	-1.0731
Kurtosis	4.3565	3.9992	3.4671	26.5880	19.2500	11.5687
Jarque-Bera	68.5466	229.0998	15.7404	18564.320	8911.8340	2548.9370
(p value)	0.0000	0.0000	0.0004	0.0000	0.0000	0.0000
ADF test	-3.4276	-2.5858	-3.2140	-6.7032	-6.2662	-9.5897
(p value)	(0.0485)	(0.2870)	(0.0824)	(0.0000)	(0.0000)	(0.0000)

4 Analysis of Results Obtained

With regards the idiosyncratic risk of the Brazilian market, the time series was estimated using the market model for mean and an EGARCH (p, q, r) model for variance.

In this market model, according to the descriptions in Section 3, the returns of the profitability index of the Brazilian stock markets, given by the stock profitability index MSCI-Brazil (MSCI-Br) as a response variable and the market portfolio given by the MSCI-ACWorld (ACW) index as a regressor. The market model selected was the model without intercept. Thus, the selected model was similar to that described by the expressions in (9), without the α parameter, with the EGARCH (1,1,1) model replacing the expression (10), since this model was selected using the criterion AIC. This model was selected among the 18 models with all the significant parameters among the 175 models estimated with different combinations, that is, varying: the estimation of the constant parameter in the average model; the probability distribution of stochastic terms, normal or Student's t; inclusion of dummy variables, in the average and or variance; and the volatility model. Additionally, as observed from the Pan American Health Organization (PAHO) information at https://www.paho.org/bra, these variable dummies considers the follow dates: January 23rd, the day of the first lockdown in Wuhan in China; January 30th, the day of outbreak declaration from the World Health Organization - WHO, that declares that the outbreak of the new corona-virus is a Public Health Emergency of International Importance (ESPII) and it is spreads for 19 countries; February 26th, the day of the first case of Covid-19 in the São Paulo city -- Brazil, a patient coming from Italy; and March 11th, the day of the characterization of the Covid-19 Pandemic by the World Health Organization - WHO. The variable dummies were added to the market model in the mean and / or variance, however none of these models were selected to estimate the idiosyncratic risk of the Brazilian economic activity.

Therefore the idiosyncratic risk used, hereafter IDR, was obtained by estimating the market model without intercept term in the average, where the stochastic terms adjusted to a Student's t distribution with approximately 6 degrees of freedom and an EGARCH (1,1,1) model for the variance. The selected model is described in expressions (11) and (12), ahead, with the estimates and the necessary metrics to observe the performance of the estimates obtained listed in (13).

mean

$$MSCI\text{-}Br_t = 1.2433\ ACW_t \quad (11)$$

se (0.0592)
t (20.9870)
p-value (0.0000)

variance

$$ln\sigma_t^2 = -0.2504 + 0.1294\ ln\sigma_{t-1}^2 - 0.0553\left|\frac{e_{t-1}}{\sigma_{t-1}}\right| + 0.9814\frac{e_{t-i}}{\sigma_{t-i}} \quad (12)$$

se	(0.0713)	(0.0327)	(0.0201)	(0.0072)
t	(-3.5121)	(3.9625)	(-2.7541)	(138.2680)
p-value	(0.0004)	(0.0001)	(0.0059)	(0.0000)

t distribution	6.48 *degree of freedom*		(13)
R^2	= 0.4636		
SE regression	= 0.0174	*Sum Squared Resid* = 0.2379	
Durbin-Watson	= 2.1010	*Akaike Information Criterion* = -5.5364	

The market model for emerging countries was estimated, to compare with the results obtained for the IDR Brazil time series. Thus, the same methodology was used to obtain the IDR Brazil using the MSCI-Emerging index (MSCI-Em), in that way obtain estimates for IDR-Emerging. From 18 estimated models, the results pointed to the selection of the market model whose results are shown forward. The model selected, using the AIC criterion, it is described in expressions (14) and (15), respectively, for the mean and for the variance, given by a GARCH model, and the performance metrics listed in (16) in the follow.

mean $MSCI\text{-}Em_t = 0.8142\ ACW_t$
se (0.0232) (14)
Stat t (35.1654)
p-value (0.0000)

variance $\sigma_t^2 = 1.84 \times 10^{-6} + 0.0864\ e_{t-1}^2 + 0.8764\ \sigma_{t-1}^2$

se	(7.45×10^{-7})	(0.0232)	(0.0305)
Stat t	(2.4652)	(3.7285)	(28.7151)
p-value	(0.0137)	(0.0002)	(0.0000)

(15)

t distribution 7.49 *degree of freedom* (16)
R^2 = 0.5177
SE regression = 0.0074 *Sum Squared Resid* = 0.0428
Durbin-Watson = 2.4399 *Akaike Information Criterion* = -7.2559

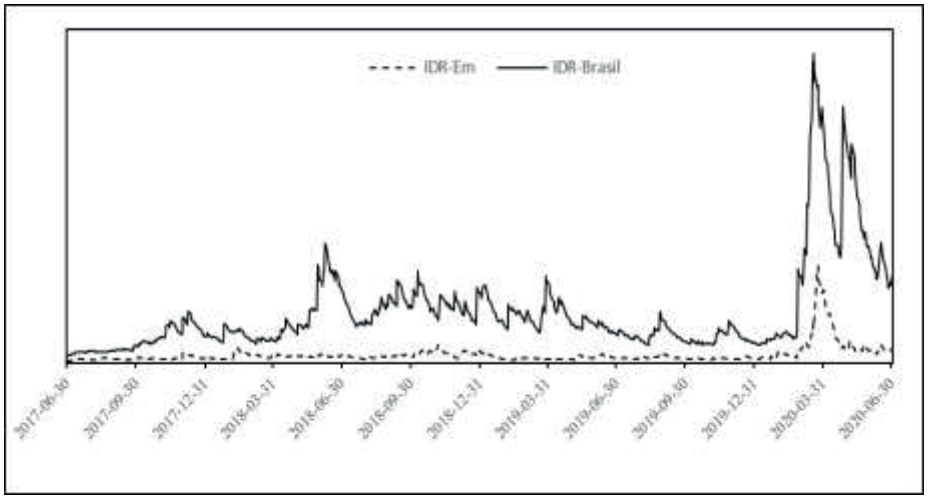

Fig. 1.The Idiosyncratic Risk of the Brazilian Market and the Emerging Markets (June 2017 July 2020)

Thus, the IDR-Brazil and the IDR-Emerging were obtained from the market model, respectively, for the Brazil and for the emerging countries. The two plots in the Fig. 1 illustrates the IDR-Brazil and the IDR-Emerging time series behavior. Regard to IDR-Brazil, it is can be to observe the risk associated with in-vestments and financing of economic activities in Brazil. In the period near the end of the first half of 2018 can be observes an increase with variations until the same period in 2019, maintaining a lower level with peaks close to the beginning of September and December 2019. At the end of February 2020, the IDR-Brazil plot shows an atypical behavior reaching a peak, the highest level in the period studied, on March 17th, 2020 after March 11th, when the Covid-19 epidemic was characterized as a Pandemic by WHO. At the end of April 2020, the IDR-Brazil decreased and then growing until the end of this month. From Fig. 1, it can be inferred that the IDR-Brazil is always above the idiosyncratic risk of the group or the portfolio of emerging countries. Another relevant inference from the observation of IDR-Brazil behavior can be done at the end of the period studied, that is, on June 30th, 2020 when the lowest level of risk in the period after the decree of the Covid-19 Pandemic by WHO was reached, which corresponds to the highest level the idiosyncratic risk of emerging countries that happened on March 23rd, 2020.

5 Conclusions and Final Remarks

This work aimed to carry out initial studies of the impacts of the Covid-19 Pandemic on national economies through idiosyncratic risk, associated with economic activity in Brazil and in emerging economies. The primary objective of this paper was to verify this impact on Brazilian economic activity. This work used a methodological approach based on the portfolio theory, a fundamental milestone of the finance theory, to obtain estimates of the idiosyncratic risk associated with the financing and investment of economic activity in Brazil, or the productive projects implemented in the Brazilian economy.

One of the two installments of the total risk of an asset portfolio, or of an economy, is the idiosyncratic risk, allowing to observe the part of the total risk that refers only to the asset portfolio or to a particular national economy. Thus, once the idiosyncratic risk can be estimated thought the market model, heteroscedastic market models were estimated for a portfolio of assets in the Brazilian economy and for a portfolio of assets traded in emerging countries. In addition to heteroscedastic conditional models, Student's t distribution was used in these models as an alternative to the normal distribution for the stochastic terms.

The idiosyncratic risk time series estimated allowed to observe the impact or influence of the Covid-19 Pandemic on the risk of the Brazilian economic activities and the emerging economies over the studied period.

It should be emphasized that the allocation of resources in productive projects, or in national economies, occurs by observing the trade-off risk and return. This way, resource managers available for applications in the international market seek to invest in projects and in national economies that can offer returns compatible with the level of risk that is externalized in the international market. The level of specific or idiosyncratic

risk associated with economic activity in Brazil demonstrated itself well above the risk of other emerging countries, in the entire period of the sample studied, which was accentuated by the Covid-19 Pandemic.

Future works can be done with other samples and methodologies that will provide more accurate results to allow for further subsidies that will contribute to minimize the Covid-19 Pandemic effects in the economic activities, particularly the financing and investment of production.

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Gas turbines inlet air cooling: mathematical analysis of Brazilian Navy's ships propulsion efficiency

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Abstract. Among the operating conditions that impact the performance of a gas turbine, the ambient conditions are the most egregious ones. Inlet air cooling systems can be used to restore these values to a level closer to the turbine's design conditions. The most used inlet cooling methods in thermal power plants are evaporative cooling, vapor-compression refrigeration systems and absorption chilling. This work investigated the application of these methods to the gas turbines used for ship propulsion in the Brazilian Navy. A mathematical model was developed and implemented on the Engineering Equation Solver for the calculation of the chilled turbines' cycle. Results were calculated respective to a design point and the inlet cooling methods were compared according to their respective effect on the gas turbines' power, efficiency and fuel consumption. Finally, a strong correlation between the ambient condition and the necessary cooling load for reaching a given temperature was detected. Therefore, this paper has great relevance to society, because the methodology presented can be used to gain efficiency in several areas of the civil and military sectors.

Keywords: Gas turbines; chilling; evaporative cooling; thermal efficiency.

1 Introduction

The study of thermal machines is usually about optimization problems: how to extract more useful work from the least energy input. The ambient conditions are so relevant for this kind of study when dealing with Gas Turbines (GT) that for commercial turbines comparison the ISO 3977-2 standard (Gas Turbines – Procurement – Part 2: Standard Reference Conditions and Ratings) defines the reference conditions. Catalog and datasheet values all account for ISO conditions, which include 15 °C temperature, sea-level atmospheric pressure and 60% relative humidity (RH).

These factors are related to the intake-air specific volume. Since power output is proportional to air mass flow and this, in turn, is inversely proportional to temperature

and greater RH results in greater heat capacity of the working fluid, which lowers the combustion exit temperature for the same energy input, the effects of variations on these conditions becomes clear, as shown in Fig. 1:

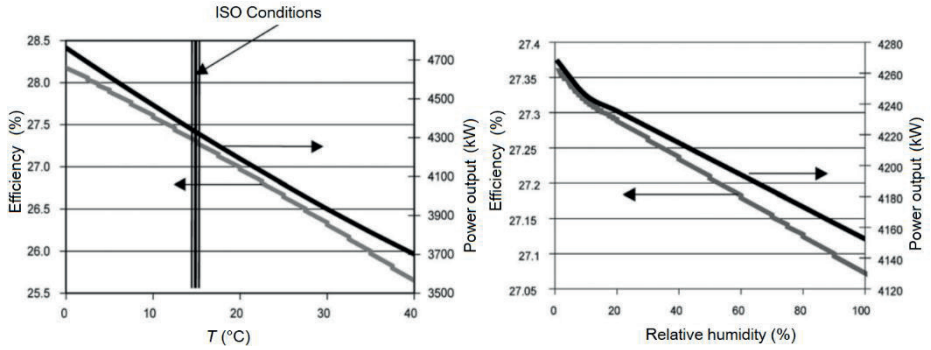

Fig. 1. Ambient conditions effects on Gas Turbines [1].

Although GT are low-efficiency machines, when compared to diesel engines or steam plants, the number of marine GT in operation around the world is on the rise, either on propulsive plants or onboard power generation. Therefore, the impact of their efficiency cannot be dismissed, because it is associated with fuel consumption in maneuvers, logistic and even strategic decisions, when the equipment life cycle is taken into account. Elevated operating costs can turn the use of GT prohibitive. Even a small increase in thermal efficiency will result in fuel economy, greater plant availability and should be taken into account not only in ships already in operation but also in the design and selection of future ships.

Ambient temperature is both the parameter which has a greater effect in a GT's efficiency and the most easily modifiable thermodynamic parameter in operating conditions, requiring only the installation of a compressor inlet air cooler, which is itself external to the GT's design.

In this study, the three main compressor inlet air cooling methods were reviewed and modeled, coupled with the Brazilian Navy's propulsion gas turbines in operation, in order to demonstrate their effects on power output and specific fuel consumption and verify their applicability in the paradigm of naval propulsion. The analysis was done through a computer simulation of the cooled GT with varying ambient temperatures.

2 Mathematical model and simulation parameters

2.1 Gas turbines and thermodynamic cycle

Gas turbine-powered vessels in the Brazilian Navy are the ones labeled as escort ships, which benefit the most from the high power and maneuverability provided by these equipments. Three types of turbines are presently in use among four classes of vessels:

• Rolls-Royce Marine Olympus TM3B: Niterói and Greenhalgh-class Frigates boost turbine;
• Rolls-Royce Marine Tyne RM1C: Greenhalgh-class Frigate cruise turbine; and
• General Electric LM2500: Inhaúma and Barroso-class Corvettes boost turbine.

The air-standard Brayton cycle is the model thermodynamic cycle in GT studies. It is thus called because assumes that the working fluid is a fixed mass of air, modeled as an ideal gas with constant specific heat, that undergoes four steady-state thermodynamic processes: adiabatic and internally reversible (isentropic) compression, isobaric heat addition, isentropic expansion at the turbine for work output and isobaric heat loss to the surroundings, thus going back to its initial state. The thermal efficiency is defined as the ratio of work output at the turbine shaft to energy input as heat. With the Brayton cycle assumptions, the effect of the intake-air temperature T_1 on the GT performance becomes evident (1):

$$\eta_{th} = \frac{W_{net}}{\dot{Q}_H} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}} \tag{1}$$

k being the working fluid specific heat ratio c_p/c_v. Thermal efficiency is also dependent on the cycle's pressure ratio P_2/P_1.

A real cycle diverges from the Brayton model in the assumptions it makes about its processes. Compression and expansion are not modeled as isentropic, so the component isentropic efficiencies η_c (compressor) and η_t (turbine) must be taken into account. Modeling these processes as polytropic, their isentropic efficiencies become a function of the polytropic efficiency η_p as follows (2), (3) [2]:

$$\eta_c = \frac{(P_2/P_1)^{\frac{k-1}{k}} - 1}{(P_2/P_1)^{\frac{k-1}{\eta_{p,c} k}} - 1} \tag{2}$$

$$\eta_t = \frac{1 - (P_3/P_4)^{-\frac{\eta_{p,t}(k-1)}{k}}}{1 - (P_3/P_4)^{-\frac{k-1}{k}}} \tag{3}$$

Still using the ideal gas model for the working fluid, the temperature difference resulting from the compression/expansion processes can be found by (4) and (5):

$$\Delta T_c = T_2 - T_1 = \frac{T_1}{\eta_c}\left[(P_2/P_1)^{\frac{k-1}{k}} - 1\right] \tag{4}$$

$$\Delta T_t = T_4 - T_3 = \eta_t T_3 \left[(P_3/P_4)^{-\frac{k-1}{k}} - 1\right] \tag{5}$$

By knowing pressure and temperature before and after all processes, and therefore fully defining these thermodynamic states, the processes themselves can be modeled by the first law of thermodynamics (6), (7), (8):

$$\dot{W}_{\mathrm{C}} = \dot{m}(h_1 - h_2) \tag{6}$$

$$\dot{Q}_{\mathrm{H}} = (\dot{m} + \dot{m}_{\mathrm{f}})(h_3 - h_2) \tag{7}$$

$$\dot{W}_{\mathrm{T}} = (\dot{m} + \dot{m}_{\mathrm{f}})(h_3 - h_4) \tag{8}$$

$\dot{m}$ being the air mass flow and $\dot{m}_{\mathrm{f}}$ the mass of burnt fuel, calculated iteratively from the fuel's Lower Heating Value (LHV) and the needed energy input rate (9):

$$\dot{m}_{\mathrm{f}} = \dot{Q}_{\mathrm{H}}/LHV \tag{9}$$

The studied GT parameters are the ones from Table 1. The compressors' polytropic efficiency was taken to be 0,9 as a starting value for calculating the isentropic efficiencies, using an iterative procedure that forced the calculated quantities to converge to the GT known datasheet parameters at ISO conditions. For fuel mass flow calculations, it was used diesel oil with a LHV of 42259,41 kJ/kg.

Table 1. ISO-condition data for the studied GT [3 - 5].

	LM2500	OLYMPUS TM3B	TYNE RM1C
P_2/P_1	18,00	10,37	12,00
T_3	-	946,8 °C	1006,8 °C
T_4	566,0 °C	-	-
$\dot{m}_{\mathrm{air}}$	70,5 kg/s	103,42 kg/s	19,05 kg/s
$\dot{W}_{\mathrm{net}}$	25,06 MW	20,88 MW	4,00 MW
η	0,3709	0,2800	0,2690

Intake-air was modeled as humid air with a mass flow rate proportional to the ISO flow rate (10) and the combustion gases were modeled as a mixture of nitrogen (75,738%), oxygen (14,141%), carbon dioxide (4,128%), argon (0,902%) and water vapor (5,091%) with the typical molar ratios for a diesel GT [6]. Except for water vapor, which followed its proper thermodynamic tables, other components were modeled as ideal gases. Specific heat values used for air and combustion gases were, respectively, 1,399 (for ISO conditions) and 1,328 (for the average combustion temperature and pressure of the three studied GT).

$$\dot{m}_{\mathrm{air}} = \frac{\rho_1}{\rho_{\mathrm{iso}}} \dot{m}_{\mathrm{air,ISO}} \tag{10}$$

2.2 Cooling methods

Evaporative cooling. This is a constant wet-bulb process that takes advantage of the latent heat of vaporization to cool an air stream. This method is used on many dry-climate power plants for inlet air cooling because it can do so with a relatively low

energy cost [7]. Air temperature after the inlet cooler and the heat removal rate can be calculated as follows (11), (12):

$$T_1 = T_0 - E\left(T_0 - T_{0,\text{wet-bulb}}\right) \tag{11}$$

$$\dot{Q}_{\text{EC}} = \dot{m}_{\text{air}}(\omega_1 - \omega_0)\left(h_{\text{H2O},0} - h_{\text{H2O,wet-bulb,saturation}}\right) \tag{12}$$

The model considered an evaporative panel with constant effectivity E of 0,85 and a feedwater pump with a 15 m head, this pump's power being the only energy input in this system.

Vapor compression chilling. This is the most widely used method for producing cold. It consists of a compressor-driven plant that takes electric power to drive a refrigerant that undergoes a phase transition to absorb heat. The heat removal rate (cooling load) can be calculated as follows and, coupled with the refrigeration plant's coefficient of performance, can be used to calculate the compressor power consumption (13), (14):

$$\dot{Q}_{\text{VC}} = \dot{m}_{\text{air}}(h_0 - h_1) - \dot{m}_{\text{air}}(\omega_0 - \omega_1)h_{\text{H2O}} \tag{13}$$

$$\dot{W}_{\text{el. comp}} = \dot{Q}_{\text{VC}}/COP \tag{14}$$

The model was based on the air conditioning plant installed on Amazon-class Ocean Patrol Ships, vessels with dimensions and displacement comparable to corvettes, the parameters of which are found in Table 2. Besides the power consumed by the compressor, it was also taken into account a condensate pump, with a pressure differential of 60 kPa, and a cold-water pump with a pressure drop of 70 kPa.

Table 2. Main parameters of Amazonas-class ship refrigeration plants [8].

Condenser heat rejection (nominal):	266,0 kW	Cold water temperature:	6,5 °C
Evaporator heat absorption (nominal):	216,0 kW	Cold water return temperature:	12,5 °C
COP:	4,32	Cold water pressure:	600 kPa

Absorption chilling. Absorption cycles allow for the production of cold water from a heat source by means of a thermochemical absorption of a refrigerant by a secondary substance, called absorbent, forming a liquid solution that is then pumped to a higher pressure. Since the working fluid is an incompressible liquid, the power consumption in this process is significatively lower than for a vapor compression process. Cooling load is calculated analogously to the vapor compression cycle (15):

$$\dot{Q}_{\text{AC}} = \dot{m}_{\text{air}}(h_0 - h_1) - \dot{m}_{\text{air}}(\omega_0 - \omega_1)h_{\text{H2O}} \tag{15}$$

The model considered the installation of a Carrier Corporation 16LJ-A series industrial absorption chiller driven by hot water heated by the GT combustion gases. The refrigerators in this series vary in cooling capacity, but all operate under the same parameters, which can be found in Table 3. The refrigerator's internal pumps consume an average of 9,7 kW. The hot water pump was considered to work on a pressure drop of

30 kPa, while the cold water and condensate pump used the same parameters as the vapor compression cycle ones.

Table 3. Main parameters of 16LJ-A series absorption chillers [9].

COP:	0,78	Cold water pressure:	1 MPa
Cold water temperature:	7,0 °C	Hot water temperature:	80,0 °C
Cold water return temperature:	12,0 °C	Hot water return temperature:	90,0 °C

2.3 Heat exchanger

The chilling systems would need to employ a coil to circulate the cold water inside the compressor inlet duct to cool the intake-air. A cross-flow heat exchanger like this can have its performance estimated by the effectivity method (16) [10]:

$$\varepsilon_{\text{coil}} = \dot{Q}/\text{MIN}(\dot{m}_{\text{i}}\Delta h_{\text{max}}) \tag{16}$$

where Δh_{max} is the enthalpy difference between both fluids (air and water) initial temperature, evaluated for whichever fluid i outputs the lowest value (MIN function), because it's the fluid with the lowest heat capacity that will be able to undergo the maximum temperature variation at the heat exchanger. From a design condition, it is possible to calculate the effectivity of the heat exchanger and, with this, the real heat exchange rate outside the design point. The heat exchange rate can be used to ascertain the enthalpy (and, assuming a constant pressure process, the entire thermodynamic state) of the air after the heat exchanger, through an iterative convergence procedure (17):

$$h_1 = \frac{\dot{m}_{\text{air}}h_0 - \varepsilon_{\text{coil}}Q\text{MIN}(\dot{m}_{\text{i}}\Delta h_{\text{max}}) - \dot{m}_{\text{cond}}h_{\text{H2O}}}{\dot{m}_{\text{air}}} \tag{17}$$

2.4 Pumps

The power consumption for hydraulic pumps is comparatively low since it's proportional to the fluid's specific volume v, which is low for liquids. The pressure difference ΔP in water circulation systems will be simply the system's pressure drop. All pumps were considered to be powered by electric engines and to have a global efficiency η_{p} (considering electric, mechanical and hydraulic losses) with a value of 0,75. Considering the water to be an incompressible fluid, the consumed power for each pump will be (18):

$$\dot{W}_{\text{el, pump}} = \dot{m}v\Delta P/\eta_{\text{p}} \tag{18}$$

2.5 Ambient conditions and design point

For Rio de Janeiro's littoral, the Brazilian Navy's main area of operations, the average maximum temperature is 30,2 °C for the hottest months [11]. To guarantee an improved performance for conditions even above the average maximum, let us define the

refrigeration systems' design point as the capacity to bring the intake air's temperature to 15 °C down from 35 °C. Rio de Janeiro's relative humidity changes little around the year, so the yearly average of 79,1% was used for the simulation.

2.6 Power generation and global efficiency

The power onboard ships are provided by diesel-generators that are, in general, more efficient than the propulsion GT. The simulation considered a naval generator set with global efficiency η_{el} of 0,412. Taking into account that the fuel used for the generator is the same kind used for the GT, the fuel consumption for the powering of the electric equipments used for the chilling systems will be (19):

$$\dot{m}_{\text{f,el}} = \dot{W}_{\text{el}}/(\eta_{\text{el}} LHV) \tag{19}$$

The total fuel consumption, therefore, is the sum of the GT's consumption and the generator's consumption. With this, it is possible to calculate the global efficiency of the chilled GT and its specific fuel consumption (kg/kWh) (20), (21):

$$\eta_{\text{global}} = \frac{\dot{W}_{\text{net}}}{LHV(\dot{m}_{\text{f}}+\dot{m}_{\text{f,el}})} \tag{20}$$

$$SFC_{\text{global}} = \frac{3600(\dot{m}_{\text{f}}+\dot{m}_{\text{f,el}})}{\dot{W}_{\text{net}}} \tag{21}$$

3 The computational simulation

The metrics that were used for comparing the cooling methods were the raise in power output and efficiency compared to the non-cooled GT, fuel consumption and global efficiency. An algorithm for calculating these quantities, as well as the entire cooled GT thermodynamic cycle, was programed into the Engineering Equation Solver (EES). EES is a well-known software and programming environment for the simultaneous solution of systems of nonlinear equations, which is useful for thermodynamic and heat transfer problems because it has, natively, thermodynamic tables for a variety of substances and functions to call the desired properties, making it the obvious choice for this application, but the algorithm could easily be converted to any other programming language (e.g. MATLAB), provided the necessary thermodynamic tables are loaded.

The method used was to divide the simulation in three blocks or procedures: one for calculating the GT component efficiencies and cycle temperatures from the ISO data, one for loading and calculating a chosen cooling method and, finally, one for calculating the cycle for the GT with integrated cooling for a variety of ambient temperatures.

The algorithm, shown in flowchart form in Fig. 2, used the mathematical modeling and fixed parameters described in the preceding section. The numbers in parentheses in Fig. 2 refer to the equations used in the calculation. GT ISO data, combustion gases molar ratios and other known parameters are loaded at the beginning.

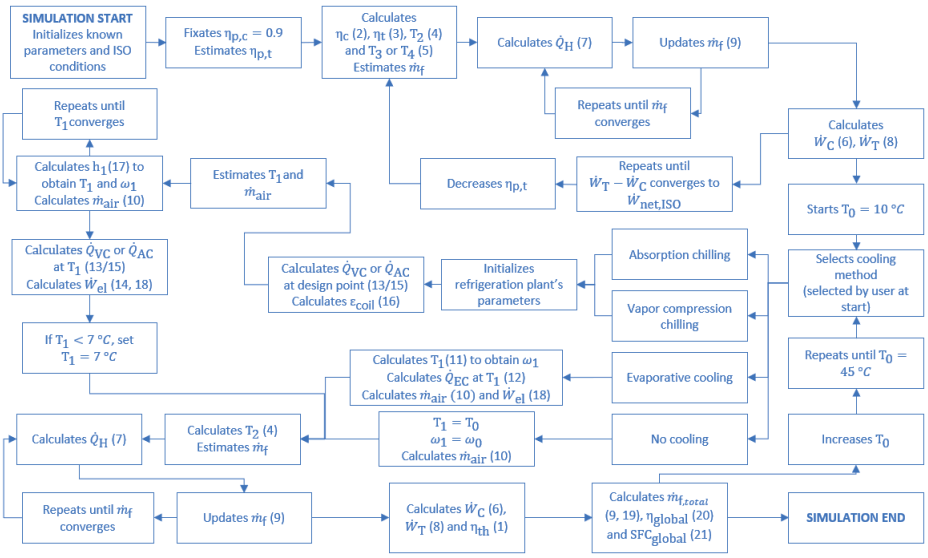

Fig. 2. Flowchart describing the simulation algorithm, with reference to the equations used.

4 Results

The heat rates of each method were calculated proportional to the airflow of each GT, to produce comparable results. The only difference in implementation for each GT would be the needed cooling load for each.

Evaporative cooling had very little effect on reducing the intake-air temperature because of the high ambient relative humidity. This is the main factor that limits its effectiveness in humid climates. The two chilling systems, on the other hand, produced equivalent cooling effects on the intake-air. The effect of this temperature drop is the rise in power output by the GT, as shown in Fig. 3 (percent nominal power).

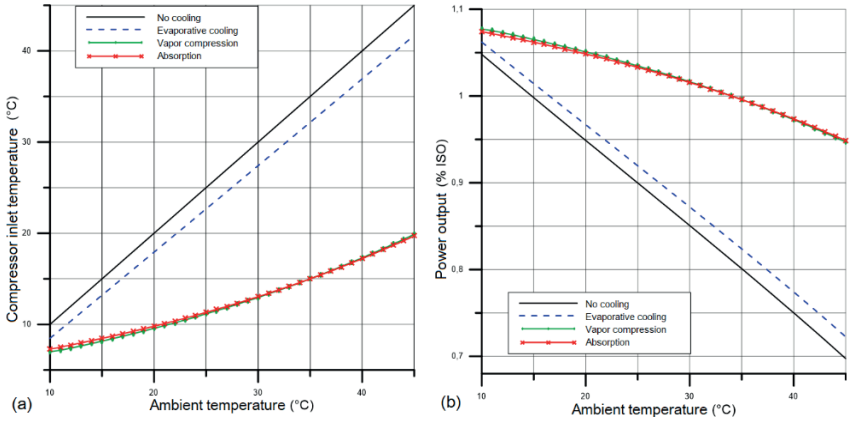

Fig. 3. Temperature drop produced by cooling methods (a) and relation to power output (b).

When considering the effect of cooling only on the GT, the efficiency curves follow the same pattern of the compressor inlet temperature curves. For global efficiency, when the entire system is considered with its energy requirements, the vapor compression and absorption curves separate drastically. As the absorption system works with fluids only in their liquid phase, the power it consumes is greatly lower than an analogous vapor compression system. Fig. 4 illustrates this result for the LM2500 GT.

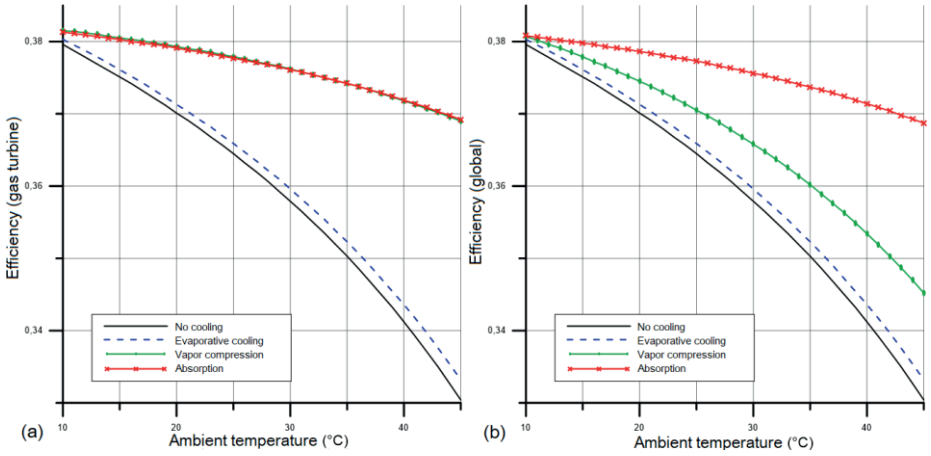

Fig. 4. GT (a) and global (b) thermal efficiency for the LM2500.

Ultimately, any deviation in the plant's efficiency will affect global fuel consumption (GT + generator). For a propulsive plant, its power output and fuel consumption are the metrics with the greatest operational relevance. Since SFC is specific per unit energy (kg/kWh), instant fuel consumption will depend on the power output in certain conditions. Fig. 5 shows both these values of consumption for the LM2500.

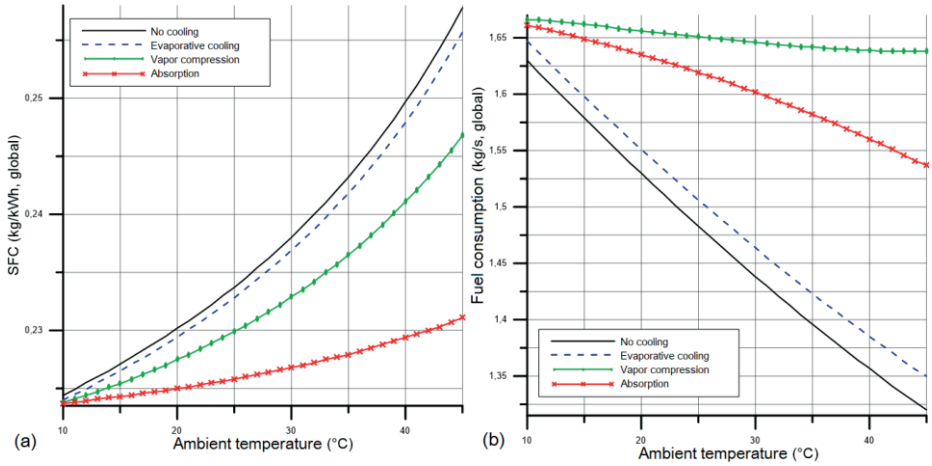

Fig. 5. Specific (a) and instant (b) chilled propulsive plant fuel consumption, for the LM2500.

Both chilling systems selected, by way of working under similar parameters for water temperature, produced equivalent gains in power output. The difference between them becomes evident when looking at their global efficiency. Despite both reaching the desired objective, the absorption system will have a lower operation cost. In a lifecycle analysis of any compressor inlet air cooling like these, in addition to the installation and maintenance costs, this is a factor that should certainly be considered.

Another important factor in military vessels is the available space for the installation of such a plant. Its dimensions will be dependent on its cooling capacity, which will be designed for a certain condition (design point). Carrier Corporation's catalogue, from which the absorption chillers parameter were taken, lists the largest in the series with a volume of 90 m³ and a nominal cooling capacity of 3956 kW, still 600 kW short of what would be needed for the LM2500 at the chosen design point.

Intake-air cooling for a GT is a much more demanding process than air conditioning, for the air mass that needs to be cooled is in constant renewal. The high demand for cooling capacity is expected and of the same order of magnitude found in literature, when the results are adjusted for the fact that the literature usually considers relative humidity of 60%. In fact, relative humidity may be the factor that affects the most the cooling load needed, owing to the condensing water latent heat. Fig. 6 shows the cooling capacity needed for a relative humidity of 79,1% (study conditions) and 60% (ISO conditions). Despite managing to produce the desired temperature drop irrespective of ambient conditions, the chilling systems are nevertheless affected by them.

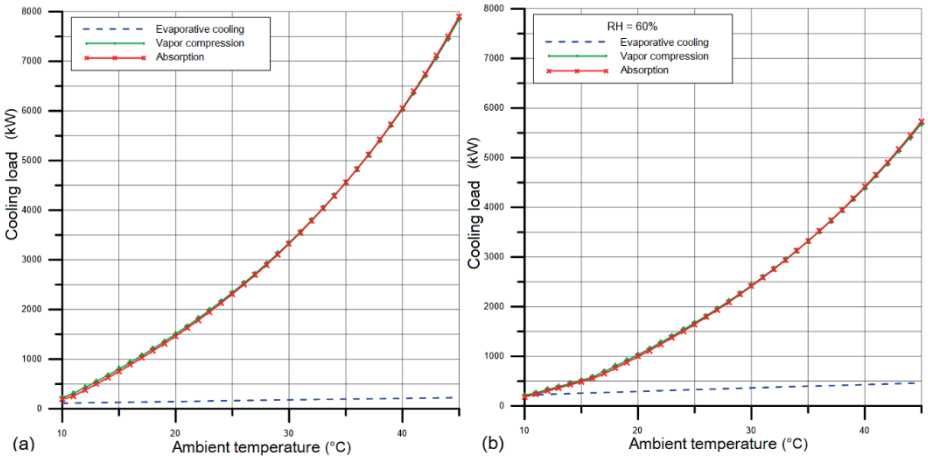

Fig. 6. Cooling load for study conditions (a) and ISO conditions (b).

The following tables summarize the results found for each of the three GT at the design point. For the evaporative cooling, even though the idea of a design point does not apply, the results shown are for T_0 = 35 °C. The values in parentheses are the percent variation over the non-cooled GT, if applicable.

Table 4. Results at the design point for the LM2500.

	Evaporative cooling	Vapor compression chilling	Absorption chilling
T_1 [°C]	32,16	15	
$\dot{Q}$ [kW]	195,9	4556	
$\dot{W}_{\text{el}}$ [kW]	0,01634	1072	35,86
$\dot{W}_{net}$ [kW]	21188 (2,52%)	24988 (20,90%)	
η_{GT}	0,3523 (0,57%)	0,3742 (6,82%)	
η_{global}	0, 3523 (0,57%)	0,3602 (2,83%)	0,3737 (6,68%)
SFC_{global} [kg/kWh]	0,2418 (-0,58%)	0,2365 (-2,75%)	0,2279 (-6,29%)
$\dot{m}_{\text{f, total}}$ [kg/s]	1,423 (1,93%)	1,642 (17,62%)	1,582 (13,32%)

Table 5. Results at design point for the Marine Olympus TM3B.

	Evaporative cooling	Vapor compression chilling	Absorption chilling
T_1 [°C]	32,16	15	
$\dot{Q}$ [kW]	287,3	6683	
$\dot{W}_{\text{el}}$ [kW]	0,02397	1572	48,08
$\dot{W}_{net}$ [kW]	17046 (2,94%)	20783 (25,51%)	
η_{GT}	0,2523 (0,96%)	0,2760 (10,44%)	
η_{global}	0,2523 (0,96%)	0,2627 (5,12%)	0,2755 (10,24%)
SFC_{global} [kg/kWh]	0,3377 (-0,91%)	0,3243 (-4,84%)	0,3092 (-9,27%)
$\dot{m}_{\text{f, total}}$ [kg/s]	1,599 (1,98%)	1,872 (19,39%)	1,785 (13,84%)

Table 6. Results at design point for the Marine Tyne RM1C.

	Evaporative cooling	Vapor compression chilling	Absorption chilling
T_1 [°C]	32,16	15	
$\dot{Q}$ [kW]	52,92	1231	
$\dot{W}_{\text{el}}$ [kW]	0,00442	289,6	16,77
$\dot{W}_{net}$ [kW]	3238 (3,09%)	3981 (26,74%)	
η_{GT}	0,2452 (1,11%)	0,2706 (11,59%)	
η_{global}	0,2452 (1,11%)	0,2582 (6,47%)	0,2698 (11,26%)
SFC_{global} [kg/kWh]	0,3475 (-1,05%)	0,3299 (-6,06%)	0,3157 (-10,11%)
$\dot{m}_{\text{f, total}}$ [kg/s]	0,3125 (1,99%)	0,3648 (19,06%)	0,3491 (13,94%)

5 Conclusion

The results were consistent with the ones found in specialized literature, adjusted for the considered ambient conditions. The effect of these ambient conditions was demonstrated not only over the GT performance, but also the compressor inlet air cooling methods.

The gains brought by the evaporative cooling system were so insignificant that may not justify the installation of a system like this in a humid climate, even when considered its low cost. The chilling systems, on the other hand, are limited by the refrigeration capacity that can be installed aboard a military vessel, the choice of a more forgiving and adequate to the local ambient conditions would lessen this demand and still benefit the plant with some power output and efficiency increase. The ideal equilibrium

point of acceptable cooling load and desired gains would depend, besides the thermodynamic analysis, also on operational considerations and operative life cycle of the vessel in which such a system would be installed. The advantages that greater power output and, therefore, greater speed and maneuverability that chilling systems would grant the ship may override the costs of installation and operation, especially with regards to boost turbines used for maneuvers, which are not used continuously. The greatest considerations for employing chilling systems in this manner, therefore, would be the operational profile of the GT (as they do not necessarily operate continuously at full-load) and the available space for the installation of such a plant. Both these factors are of low relevance for the usage most commonly found in the literature (i.e. thermoelectric power plants).

Lastly, a reliable and precise model for simulating steady-state, full-load gas turbines, coupled with a cooling system or not, was developed and successfully applied. The algorithm presented in this paper could be used for an initial calculation in the design or selection of a cooling system for gas turbines not only in the studied scenario, but also others where GT are used, such as power generation.

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Reducing heat emission in discharge ducts and increasing the global energy efficiency through energy cogeneration

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Abstract. This paper aims to analyze a way to decrease the temperature of exhaust gases in the discharge ducts of the Inhaúma class corvettes of the Brazilian Navy. A study was carried out of the cooling, intake and exhaust systems of the engine gases used in these ships and it was possible to determine, from the temperature and flow, the energy contained in these rejected gases. In the present article, the suggestion to lower this temperature and, thus, reduce the possibility of detection of the ship by cameras or weapons that work with infrared sensors is the reuse of this energy through the implementation of a cogeneration plant. The main focus of this plant is to harness this energy available to heat water and this is used as the hot fluid in a steam generator in a selected absorption cooling cycle from available commercial catalogs, which would have the ability to meet 25% of the ship's environmental conditioning thermal load. It was emphasized on the thermal design and sizing of the heat recuperator, as this has the essential function of transferring the initially lost energy to another heat supply process.

Keywords: Cogeneration energy, Heat transfer, Heat recovery, Exhaust gases.

1 Introduction

The combustion gases with high temperatures are used in several areas both in the industrial and tertiary sectors in systems called energy cogeneration. Cogeneration "is the combined production of work and thermal energy from the sequential use of energy from a fuel", according to the definition of the Public Utilities and Regulatory Policies Act – PURPA [1]. The more efficient use of the same primary energy source reduces the temperature of discharge gases and fuel consumption and, consequently, the cost of operation when compared to systems that produce electrical and thermal energy independently. Cogeneration systems have high global energy efficiency, usually above 70%, and lower emission of environmentally harmful substances.

The themes of energy conversion with energy recovery will have a high potential for development for naval applications. The containment of pollutant emissions can be achieved by a cycle with thermal energy cogeneration to feed the ship utilities, in place of the diesel engines currently used [2].

For some years, a few ships have been using cogeneration, however, there are several possible configurations to meet thermal, electrical and mechanical needs, making it necessary to choose the most appropriate one according to the following terms: energy use decreased temperature of exhaust gases, available space and lower emission of substances harmful to the environment.

In Brazil, the use of stealth vessels could contribute to better control of the exploitation of wealth, such as oil and fish present in the huge national maritime areas, in addition to the monitoring of maritime borders, which are fundamental for the maintenance of national sovereignty [3].

In the work, an analysis of the gases from the discharge ducts of a ship with a propulsion system similar to those used in the Inhaúma class corvettes (CCI) of the Brazilian Navy will be carried out, which present two diesel engines MTU 16V956 TB91 and a GE LM 2500 turbine. However, the use of only engines will be considered in the case under study, given that the use of the turbine is reduced and limited to situations where a large increase in power is required. However, the temperature of the discharge gases of the internal combustion engines strengthens the thermal signature and thus decreases the stealth characteristic of the vessels, as they facilitate their detection by infrared capture cameras. Also, the high temperature of these gases means fuel waste that is not renewable and has high costs.

The objective of this work is to obtain data regarding the temperature and flow of exhaust gases through the study of engines and their parameters used in the corvettes of the Brazilian Navy and, thus, to carry out a project of reuse of this energy initially discharged into the atmosphere with a high cost to supply about 25% of the total thermal load of the ship through an absorption cooling cycle.

The methodology of the work was made through an analysis of the engine design parameters. The flow of the discharge gases of the equipment was calculated by obtaining data from the operation manual and the temperature of this is data obtained directly, considering the standard working point of the engines. Through these data, it was possible to design a heat exchanger introduced at the output of the combustion gases to recover this energy and use it in a selected absorption cycle through a company catalog.

The energy recovery was designed through a cross-current core of the equipment [4]. The sizing was stipulated so that the temperature of the gases would reduce to approximately 200 °C through iterations from the area of this equipment.

2 Energy cogeneration

Cogeneration is becoming increasingly popular in energy systems with demands on electricity and heat, which is suitable for industrial use in remote areas [5]. Energy cogeneration consists of the use of the calorific value released by the fuel for the simultaneous production of mechanical, thermal or electrical energy, through the recovery

of residual heat. This increases the overall efficiency of the system. In the case of warships, with the growing search for thermal camouflage, cogeneration can also be pointed out as an effective method to reduce the temperature level of exhaust gases, making it difficult to detect by the enemy.

For the best use of residual energy, an analysis based on the second law of thermodynamics in the form of exercise balance is necessary, which may indicate away with fewer losses. The exercise balance can be used to determine the location, type and magnitude of exercise losses, and can also give us an important role in the development of strategies and provide more effective lines of action in the use of energy in existing power plants [6].

However, this work is limited to the analysis of the energies involved in the cogeneration plant by taking control volumes over the system assemblies. Thus, in this project, the concept of energy cogeneration initially presupposes the combination of three types of equipment: diesel engines already existing on the ship for the production of mechanical power responsible for propulsion, an absorption cooling system for the production of cold water and one heat recovery that enables thermal exchange between the two equipments mentioned above.

2.1 Available residual energy

The corvette propulsion system has as main components two engines and one turbine. These two equipments do not work at the same time, the combined diesel engine system (MTU 16V956 TB91) of 3,900hp is used for cruise speeds, while the gas turbine (GE LM-2500) of 27,000hp to meet high-speed demands. This type of propulsion is known as CODOG (Combined Diesel or Gas Turbine) and is quite common in warships.

CODOG propulsion allows a continuous maximum speed of 27 knots (turbine) and a maximum cruising speed of 18 knots (diesel engines). The range is about 4,000 nautical miles at 15 knots [7]. For this, the propulsion using the turbine will not be analyzed due to its low frequency of use.

The exhaust gas temperature obtained through the MTU Company Operating Manual is 550 °C for the maximum power condition (2680 kW to 1490 rot/min), but the parameters used will be in continuous power condition (2570 kW to 1470 rot/min).

In the condition of continuous power, the temperature of the residual gases is 500 °C. Another information needed to obtain the available residual energy is the flow of these gases and this data is not provided directly from the operation manual, but can be obtained by a simple calculation, since the total displacement, rotation and characteristics of the engines are known (Table 1).

Table 1. Parameters and characteristic of the engine in continuous power regime [8].

Total displacement (Cr)	152.9 liters
Rotation	1470 rot/min
Power	2570 kW
Engine type	4 times

Multiplying the total displacement by the engine speed and dividing by 2 (two), since the engine is four strokes, we determine the volumetric flow:

$$\dot{v} = \frac{C_T}{2} \tag{1}$$

Where $\dot{v} = 1{,}873\ m^3/s$.

Considering that gases leave the engine at atmospheric pressure (100 kPa), the other properties of the working fluid can be determined: Enthalpy $(h) = 793{,}1\ kJ/kg$ and Specific volume $(v) = 2{,}2\ m^3/kg$. With these properties it is possible to know the values of mass flow and energy rate of discharge gases (2), (3):

$$\dot{m} = \frac{\dot{v}}{v} = 0{,}85\ kg/s \tag{2}$$

$$\dot{Q} = \dot{m}\ h = 675{,}22\ kW \tag{3}$$

Therefore, one is aware of the rate of thermal energy available in the exhaust of an engine. As the ship understudy has two engines, the total thermal energy rate in engine exhaust is equivalent to 1350.45 kW.

2.2 Absorption cooling system

The inclusion of the absorption cooling cycle can be a viable form of energy cogeneration application, as this system uses a heat source to dissociate the refrigerant from the water inside a generator and, at the end of the cycle, a fluid can be cooled and used for environmental conditioning of the ship. This type of energy use has proved effective in other types of applications such as in the industrial and pharmaceutical sectors. For the application of this concept in this work, the residual heat from the discharge gases will become the hot source of the absorption equipment as shown in Fig. 1:

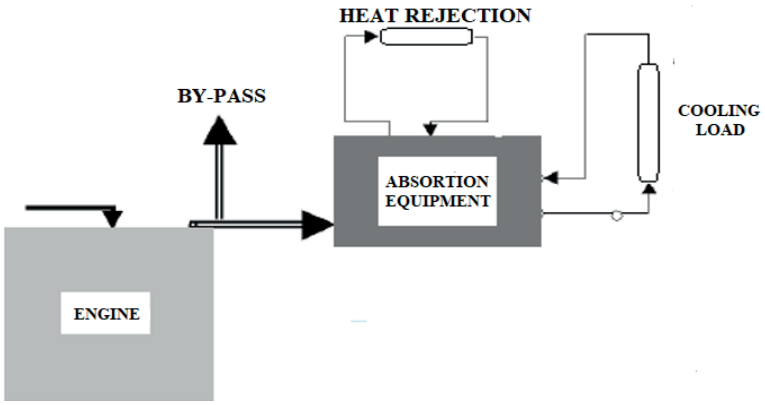

Fig. 1. Energy cogeneration scheme.

In the CCI modernization project, three URA equipments model YEWS415HA50E of Johnson Controls, with a capacity C_T of 411 tons of refrigeration (1,445.4 kW) were

installed. These URAs can operate with partial loads of 25%, 50%, 75% and 100%, and only one of these equipments can meet the need for environmental conditioning of the entire ship.

In the routine of the ship, it is observed that in a considerable period only one cooling unit is used, and with a partial load of 25 %. Due to this fact, it is plausible to select an absorption water cooling equipment with this capacity. The cooling capacity of the absorption chiller $C_t = 25\%\ C_T$; and $C_t = 380.5\ Kw$.

Through the cooling capacity, it is possible to select the cooler from catalogs of companies already established in the market. In this work, the company chiller Carrier model 16 LJA-13 was selected, whose characteristics and parameters are shown in the following table:

Table 2. Parameters of the Carrier absorption chiller model 16 LJA-13.

Equipment model	Carrier 16 LJA-13
Cooling capacity	387 kW
Ice water system	-
Mass flow	18.5 kg/s
Inlet temperature T_1	12°C
Output temperature T_2	7 °C
Hot water system	-
Mass flow	12.3 kg/s
Inlet temperature T_3	90 °C
Output temperature T_4	80 °C
Performance coefficient	0.78
Mass of equipment in operation	5200 kg (1,000 lb)

Through the catalog of the equipment already selected, some important parameters can be obtained for the sizing of the cogeneration plant, such as the required flow of hot and cold water and their respective temperatures at the inlet and outlet of the machine, and, knowing the specific heat of the water, the rate of thermal energy transferred in the generator and evaporator of the Chiller, in addition to the performance coefficient of the absorption cycle (4), (5) and (6).

$$\text{Evaporator: } \dot{Q} = \dot{m}\ c\ (T_1 - T_2) = 386{,}6\ KW \tag{4}$$

$$\text{Generator: } \dot{m} = \frac{\dot{v}}{v} = 0{,}85\ \ kg/s \tag{5}$$

$$\text{Performance coefficient (COP): } COP = \frac{\dot{Q}_{Evaporador}}{\dot{Q}_{Gerador}} = 0.75 \tag{6}$$

It appears that the calculated COP is close to that indicated by the manual. This difference is due to approximations in the value of the specific heat of the water. Other important data can also be obtained from the catalog, such as the weight of the machine, as it changes the stability of the ship and the dimensions that are critical aspects in confined environments such as ships. However, this work is limited to analyzing the energy viability of the cogeneration cycle in this system.

2.3 Heat exchanger

The design of this equipment involves many aspects. In this work, the dimensioning, heat transfer and performance evaluation will be evaluated, but the load losses and the costs of the exchanger will not be analyzed. To calculate the heat exchange area and thus select the exchanger it is necessary to know the inlet and outlet temperatures and the flow rates of the fluids.

The sizing problem refers to certain dimensions of the pipe beam to achieve the requirements of heat transfer and load loss. If we do not consider the load loss, the thermal calculation involves the determination of the total heat transfer rate to a given heat exchanger; and sizing involves determining the total heat transfer surface required to achieve the specified heat transfer rate [9].

The flow and temperature of the inlet combustion gases, as well as the flow rate and water inlet and outlet temperatures, were obtained according to (1), (2), (3) and (4).

Analyzing the data so far, it is observed that the temperature of gases after the exchanger has not yet been established. For thermal camouflage, the smaller this property, the better it would be, but exhaust gases with temperatures lower than one hundred and eighty degrees would generate other types of problems related to the environment and corrosion. Thus, initially, we can stipulate that the ideal output temperature of these components is close to two hundred degrees Celsius (Fig. 2).

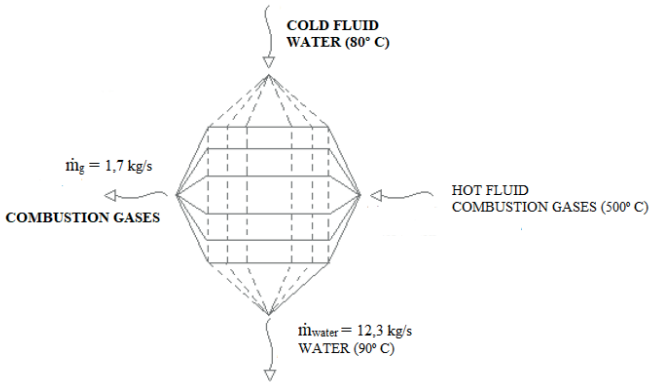

Fig.2. Heat exchanger with the indicated design parameters.

Through case studies, a compact cross current exchanger (area density greater than 700 m^{-1}) will be selected for the project due to its small size and weight. Commercially there are several configurations of heat transfer core, however, due to difficulties inherent to obtaining parameters and characteristics of commercial exchangers, in this work, an experimental exchanger studied [4] was used.

To start the calculation, we need the physical properties of the working fluids. As atmospheric air consists of approximately 79% nitrogen and ideally this element does not react in the combustion process, the properties of gases can be approximated with those of air at average temperature, but the output temperature of the gases is not known. So, we can initially estimate the temperature of the gaseous fluid at the output of the exchanger at two hundred degrees Celsius and thus the average temperature calculated would be three hundred and fifty degrees Celsius. This initial estimate can be corrected if necessary, at the end of the calculations. As the temperature of the inlet and outlet water in the exchanger is fixed, the properties were also taken in relation to the average temperature.

To calculate the coefficient of global heat transfer concerning the outside of the pipes it is necessary to know the coefficients of internal and external heat transfer and the efficiency of the fin (7).

$$\frac{1}{U_a} = \frac{1}{\dot{\eta} h_a} + \frac{1}{\left(\frac{A_w}{A_a}\right) h_w} \tag{7}$$

Where:

U_a is the global heat transfer coefficient;

$\dot{\eta}$ is the efficiency of the fin weighted by the area;

h_a is the external heat transfer coefficient; and

h_w is the internal heat transfer coefficient.

From experimental data obtained and with the value of the Reynolds number, it is possible to estimate the heat transfer coefficient [4] (8), (9).

$$Re_a = \frac{G_a D_{h\,a}}{\mu_a} \approx 2680 \tag{8}$$

$$G_a(Mass\ velocity) = \frac{m_a}{\sigma_a A_{fr}} = 24{,}25 \tag{9}$$

To determine the relationship between the Reynolds number and the heat transfer coefficient, we used the experimental data of the exchanger.

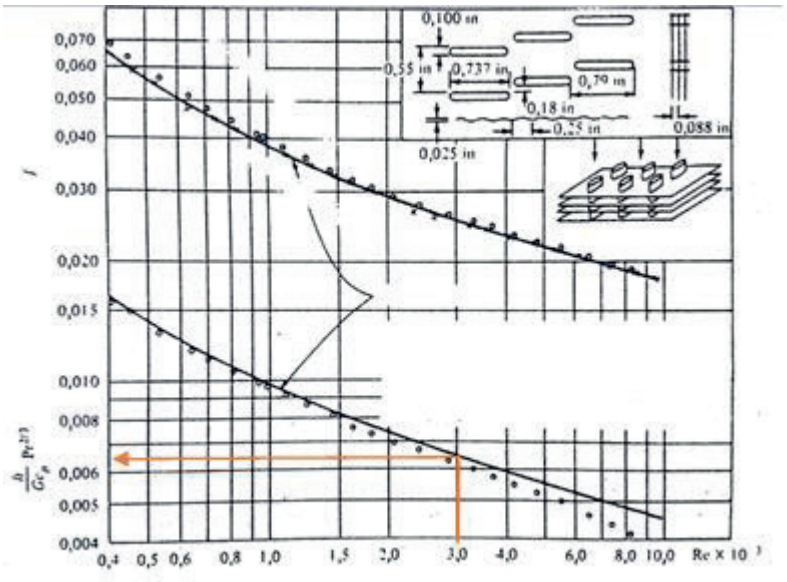

Fig.3. Heat transfer and friction factor in the flow through the heat exchanger [4].

$$\frac{h_a}{G_a c_{pa}} P_r^{\,2/3} = 0{,}0065 \tag{10}$$

Where the Internal heat transfer coefficient $h_a = 216{,}4 \frac{W}{m^{2\circ}C}$.

$$Re_w = \frac{u_{max} D_{h,w}}{v_w} = 19610 \tag{11}$$

$$u_{max}(mass\ velocity) = \frac{m_w}{\rho_w A_{fr} \sigma_w} = 1.82\ m/s \tag{12}$$

With this high value of Reynolds number, one can consider the fluid completely developed and thus use the equation, with correction due to changes in properties, to determine the relationship between the Reynolds number and the heat transfer coefficient [10] (13).

$$h_w = 0{,}027 \frac{k}{D_h} Re^{0{,}8} Pr^{\frac{1}{3}} \left(\frac{\mu_{85^\circ C}}{\mu_{90^\circ C}}\right)^{0{,}14} = 17025 \frac{W}{m^{2\circ}C} \tag{13}$$

Where:

Water viscosity (85°C) $(\mu_{85^\circ C})$: $0{,}000336 \frac{kg}{ms}$;

Water viscosity (90°C)$(\mu_{90^\circ C})$: $0{,}000318 \frac{kg}{ms}$

Therefore, in the external flow, there are flat fins and the effective difference between the temperature of the fluid and that of the fin surface is less than the difference between the fluid and the base of the fin (14), (15).

$$\eta(Fin\ thermal\ efficiency\ ) = \frac{t\ g\ h(mL_e)}{m\ L_e} = 0{,}79 \tag{14}$$

$$m = \sqrt{\frac{2h_a}{k\ t}} = 159{,}56 \tag{15}$$

With the efficiency of the fin and the ratio between the fin areas and the total area, we can calculate the efficiency of the fin weighted by the area (16).

$$\eta = \beta\eta + 1` - \beta = 0{,}82 \tag{16}$$

Once these three process parameters are known, one can then determine the overall heat transfer coefficient through (7).

After obtaining this coefficient, the flow rates and temperatures of inlet and outlet of fluids, it is possible to determine through an iterative method the value of the logarithmic average temperature difference (DTML) that satisfies the heat requirement transferred in the heat exchanger to be equal to the heat dragged by the fluid expressed by (17):

$$Q = f\ A\ U_a\ \Delta T_{ln} \tag{17}$$

Where:
f is the correction factor;
A is the heat exchanger external area.
$\Delta T_{ln} = DTML$.

Therefore, the other three parameters can be analyzed through (17).

I) Correction factor

The temperature of gas inlets is considerably higher than the water outlet temperature. Taking this into account analysis cross current heat exchangers of a pass, it is concluded that the correction factor can be considered equal to the unit [11].

II) The external area of the heat exchanger

It is a parameter that is determined iteratively along with the total heat transfer rate and the DTML. With the number of rows, the number of tubes per row and quantity of plates, the length, width and height of the equipment, and knowing the relationship between area and total volume, the iteration can take place through the distribution of rows in the exchanger.

III) Logarithmic mean temperature difference (DTML)

By an initial estimate of two hundred degrees Celsius for the gas output temperature, an initial DTML value can be determined, as shown below. With this initial value, it is possible to perform the iterative process until the values of external area, total heat transfer rate and DTML converge.

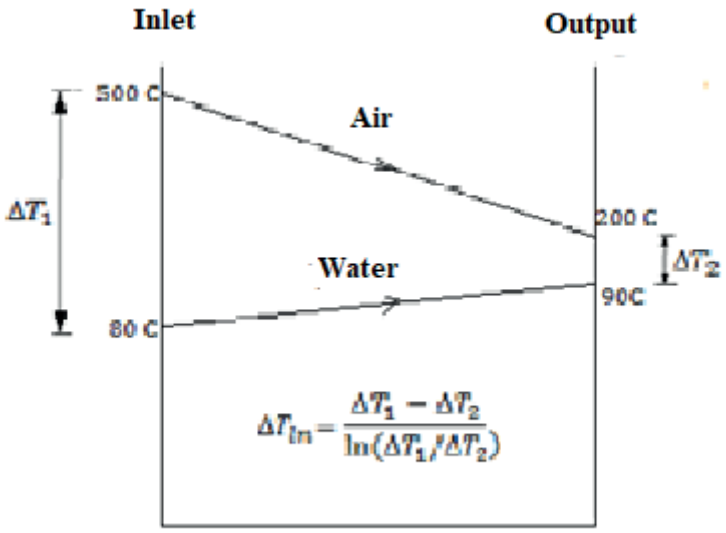

Fig. 4. Method for calculating THE DTML.

The iterative process was carried out following the following steps:

1- Estimate the gas output temperature (200 °C).

2- Calculate DTML.

3- Estimate the characteristics of the equipment (number of rows, number of tubes per row and height) and thus determine the total exchange area.

4- Determine the total heat transfer rate.

5- Determine the output temperature of the gases and compare them with the estimated in step 1.

6- If they are not close, redo the calculations at this calculated temperature.

The above steps were performed until convergence occurred. The obtained values are shown in table 3:

Table 3. Features of the designed heat exchanger and process parameters.

Heat exchanger and process feature	
Number of rows	15
Number of tubes per row	30
Number of plates (fins)	80
Heat exchanger core width	30 cm (12 in)
Length of heat exchanger kernel	30 cm (12 in)
Heat exchanger core height	17.6 cm (17.6 cm)
Total external heat exchange area	14.03 m2

Volume	0.0158 m3
Heat transfer rate	521.5 kW
DTML	224.9 °C
Heated water outlet temperature	90.1 °C
Output temperature of discharge gases	212.0 °C

The small dimensions of the equipment are due to the fact that an experimental exchanger model was used and possibly not feasible to manufacture for commercial purposes. It is also noted that the temperature is relatively close to that initially stipulated, so changes in fluid properties can be disregarded.

3 Conclusion

The study carried out in this work proposed the reduction of the temperature of exhaust gases through the implementation of an energy cogeneration plant, in which the heat contained in these gases is reused through a heat exchanger in a steam generator in an absorption cooling cycle.

As for the equipment, we studied the system and air intake and discharge of gases from internal combustion engines and through this study, it was possible to select the refrigeration equipment and then design the heat recovery that provides the thermal exchange between the gases and the water.

This proposal presented viability regarding the initial objective of reducing the temperature of gases, as well as increasing the overall efficiency of the system, as this change will be responsible for meeting 25% of the thermal load of environmental conditioning of the ship through an energy that is being wasted when being released directly into the atmosphere.

The implementation of the cogeneration plant, through this increase in efficiency, in addition to reducing the cost of operation, also reduces the consumption of non-renewable fuels making the ship more viable when considering environmental aspects.

As a suggestion for upcoming work, in addition to reducing the limitations of the previous chapter, one can also calculate the energy stored and discarded in the engine cooling and lubrication systems and reuse it in a new water heating plant used by the ship's crew.

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Process Mining and Value Stream Mapping: an incremental approach

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Abstract. Organizations of all sizes and complexities are increasingly facing a challenging environment. Competition is increasingly fierce and market dynamism requires agility in emerging issues to adapt and survive. Understanding and promoting process improvements is a necessity that has troubled managers and, these use methods and tools to support their work teams in the search to eliminate losses and waste. This article aims, from a theoretical and conceptual approach, to understand VSM, its application, main positive aspects, and problems, as well as to present concepts and premises of process mining. To study two process mapping tools that are Value Stream Mapping (VSM) and Process Mining PM showing a way to improve these approaches. Seek its foundations in a quick literature review, propose a method to apply the two tools empirically and in a case study provide the authors with evidence that indicates an incremental improvement in the mapping process.

Keywords: Process mining, Value stream mapping, Process improvement.

1 Introduction

Organizations of all sizes and complexities need continuous adaptation to changes in the global, economic, and market environments. This adaptation requires solutions that consider the organization in a systemic way, that is, its role, people, knowledge, information, processes, strategy and technology [1].

A widely used tool for seeking improvement in the process is the Value Stream Mapping (VSM), which consists of an analysis performed with a pen and paper to understand the process flows and that, at the end of the analysis, a future map can be drawn, considered ideal for the process. VSM, which has an easy language, makes it possible to evaluate both the production and information flow, allowing a real view of the process.[2]. Despite the many benefits of the tool, in complex and dynamic environments the level of difficulty in the application of VSM increases. For [3] and [4], for example, the problems of applying the tool in these environments appear mainly in the collection and updating of data, as complexity can lead to a high time for the

construction of the mapping and even so some information can be neglected. Also, continuous monitoring of flows through VSM in highly dynamic environments is often not feasible.

With the rapid evolution of technology and the constant search for innovation in organizations, new perspectives and combinations of actions are developed in search of increasing business actions and executions, among them we can mention the computerization and digitalization of equipment, activities, or processes. One of the aspects of evolution, which can be considered an increase in process improvement tools, such as VSM, is Process Mining. The idea of process mining is to discover, monitor and improve real processes (that is, unassumed processes) by extracting knowledge from the event logs available in current systems [5].

This article aims, from a theoretical and conceptual approach, to understand VSM, its application, main positive aspects, and problems, as well as to present concepts and premises of process mining. Then, process mining is proposed as an incremental approach to VSM. Based on the theoretical analysis, a practical case study was then carried out to evaluate the applicability of the obtained perceptions and the proposed method.

The structure of the article has a brief review of the literature regarding the value stream mapping and process mining in section 2. In section 3, the proposed method and the framework developed for the application of process mining are demonstrated. Section 4 shows the application of the method in a case study in the automotive industry. Finally, in section 5, discussions about the work developed are presented, followed by the conclusions in section 6 of the article.

2 Literature Review

The literature review aims to provide theoretical support about value flow mapping (VSM) and process mining (PM), raising its concepts, perspectives, application, assumptions, and vulnerabilities.

2.1 Value Stream Mapping

Value stream mapping is a paper and pen tool that helps you understand the flow of material and information as a product progresses through the value stream, helping to identify waste. For mapping, one must follow the production flow of a product, from the supplier to the customer, and carefully draw a visual representation of each process in the material and information flow. Then, a future map can be drawn of how the product should flow optimally, which will serve as the basis for an action plan. VSM concerning other techniques stands out for being able to demonstrate, in an easy language, the relationship between production and information flow both within the organization and within the supply chain. Also, the tool can provide important information such as stock levels and production time, helping to make decisions regarding production flows.[2].

From the studies by [6], it can be inferred that although it has numerous advantages, VSM has some limitations. First, it can be a big challenge when it comes to

a complex product or process. The level of difficulty in preparing the VSM can be high due to the high effort involved in data collection and the time spent in building the mapping of the current state. Also, the existing complexity and possible invisibilities of the process can prevent the collection of sufficient data by direct observation. Another factor is that VSM is a static method, based on paper and pen, so its precision level and dynamic capture capacity are limited. Thus, many companies fail to apply the value flow mapping continuously, as there are always changes in products and processes. However, to obtain improvement effects, continuous monitoring is necessary for several months.

To better understand the difficulties experienced with the use of VSM, the present work brings some important information taken from a set of articles where the VSM was applied, and from which it was possible to remove some problems identified when applying the tool. These works were found through a brief survey on the problems related to VSM and brought several characteristics that were grouped into 7 categories.

1. Non-integrated processes: lack of integration between processes makes it difficult to analyze the value flow.
2. Lack of standardization and stability: processes are not clear. Existence of more than one material flow in the same line.
3. Poor understanding of the Lean principles and VSM: there is no deep understanding of the basic concepts of the tools.
4. Difficulty in measuring in-process data: problems with layout, complexity of product and process, which end up making it difficult to measure data in-process.
5. Current flow map out of date: Process that changed over time without updating documents.
6. Very flexible production: constant change to meet market demand: production mix with small batches, and many products assembled on the same line.
7. Process performed intuitively: process flow depends on the tacit knowledge of the operator, deciding in real-time how the product enters the flow.

In addition to the problems reported in the categories presented, some authors still cite possible causes for the problems encountered when applying VSM as; the increase in the product portfolio offered by the companies, the difficulty in choosing one of the products to be evaluated by the VSM, and the lack of a holistic view of the managers, who are unable to see the importance of making their processes clear to the partners. Other factors pointed out are the lack of process stability, errors in data measurements, product/process complexity and their obsolescence [3][4][7].

Table 1. *List of problems cited by authors in the application of VSM.*

Problems	Authors
Non-integrated processes	[8]; [3]; [4]; [9]; [10]; [11]; [7] [7]
Lack of standardization and stability	[3]; [12]; [10]; [13]; [11]
Poor understanding of the Lean principles and VSM	[14]; [2]; [8]; [9]; [10]; [15] [13]; [16]; [17]; [18]; [7]
Difficulty in measuring in-process data	[14]; [2]; [8]; [19]; [3]; [15]; [20]; [13]; [21]; [11]; [17]; [12]; [7]
Current flow map out of date	[2]; [3]; [13]; [7]
Very flexible production	[14]; [2]; [8]; [3]; [4]; [9]; [10]; [20]; [22]; [11]; [16] [17]; [7]
Process performed intuitively	[8]; [3]; [10]; [15]

As can be seen in the problems pointed out by the authors, for an effective VSM that can provide support for decision making, it is necessary that the company has a well-structured process and can update the VSM frequently, as today companies have an increasingly short product life cycle, which makes VSM obsolete quickly. Besides, Table 1 shows that one of the most pointed problems in the literature is the difficulty in measuring data in-process. Because of this, this article proposes the use of process mining as a tool capable of assisting in data collection and process mapping, allowing a faster and more assertive update of the value flow map.

2.2 Process Mining

Clearly, process models play an important organizational role. The modeling of processes and/or workflows, as in the case of VSM, seeks to reflect an alignment between what is modeled and what actually occurs in real age. Unfortunately, many of the "hand-made" methods do not have this desired connection, showing only an idealized view of the facts [23]. The re-design and process innovation approaches can present a failure indicator of 60-70%, since most of these approaches are subjective,

incomplete and require high availability of time and resources, since they are based on interviews and observations of actors involved in the process [24].

Organizations face constant challenges to maintain competitiveness and process improvement initiatives, such as VSM, are often conducted in search of improvement in the efficiency and effectiveness of processes. Process mining presents itself as an important facilitator of continuous process improvement, as the use of the event log can be used as information evidence of processes [25].

Process mining offers an interesting approach that seeks to solve or mitigate these problems. As organizations depend on information systems that support activities, they can record a large amount of data, for example: which activities were performed, who performed them, when they were performed. This event data can be organized as a path that contains the history of what, in fact, occurs during the execution of a process. This history can be analyzed using process mining techniques [26]. It is a relatively young research discipline, between machine learning and data mining, on the one hand, and process modeling and analysis, on the other. The idea of process mining is to discover, monitor, and improve real processes (that is, unassumed processes) by extracting knowledge from the event logs available in current systems [5].

The collection of information about the processes, from the information systems, when performed automatically reduces the time of analysis of the processes. Even so, the main benefit of process mining techniques is the possibility of analyzing a model based on the actual execution of the steps. Therefore, the insights obtained during the analysis, as well as the knowledge acquired, can be used to effectively improve the processes submitted to mining techniques. The event data can be analyzed according to different perspectives: (1) the flow-control perspective; (2) the organizational perspective; (3) the data perspective; and (4) performance perspective. The flow-control perspective is concerned with the behavior of the process, namely, the process and its order of execution. The organizational perspective focuses on the relationships between users who performed the activities, as if they belong to the same group or to different groups or organizational units. The data perspective is related to the data objects that serve as input and output for the activities in a case. The performance perspective aims to detect bottlenecks or calculate performance indicators, such as production times and, therefore, recording times [26].

Another possible use for process mining is conformity assessment, which consists of comparing a hand-drawn model (eg, VSM, BPM, VBM) with its event log. The compliance check can be used to determine efficiency and raise proposals for improvement in the face of an established process [27]. The quality of the process, generally, takes into account factors of case behavior, precision, generalization, and simplicity [23].

This mining application supports decision makers on issues such as time spent passing cases through the process, transitions and intermediary decision making, time consumed at each stage, critical activities and resources and time between activities [28]. Decision-makers in organizations show great interest in mining processes by realizing the high added value for the business and the possibility of insights brought about during process improvement studies [29].

3 Methodology

The methodology seeks to establish empirically, through a case study, improvements in the mapping of the value stream, which, despite being widespread and with satisfactory results, can still evolve with the increment of process mining. The study is carried out in two phases, being: first the execution of the VSM according to the steps in figure 1, which are: specify the customer data; place the functions and departments involved; identify units that trigger the process; record the main steps; evaluate the stages, interfaces and information flows of the process; register flows of external material and services; insert the timeline.

The second phase consists of the application of process mining in the process previously analyzed by VSM. The steps of process mining are performed according to figure 1, which are: extraction of the event log; analysis of the event log; process analysis; and results. The methodology can also be used in similar processes where it is possible to remove the event log from the database.

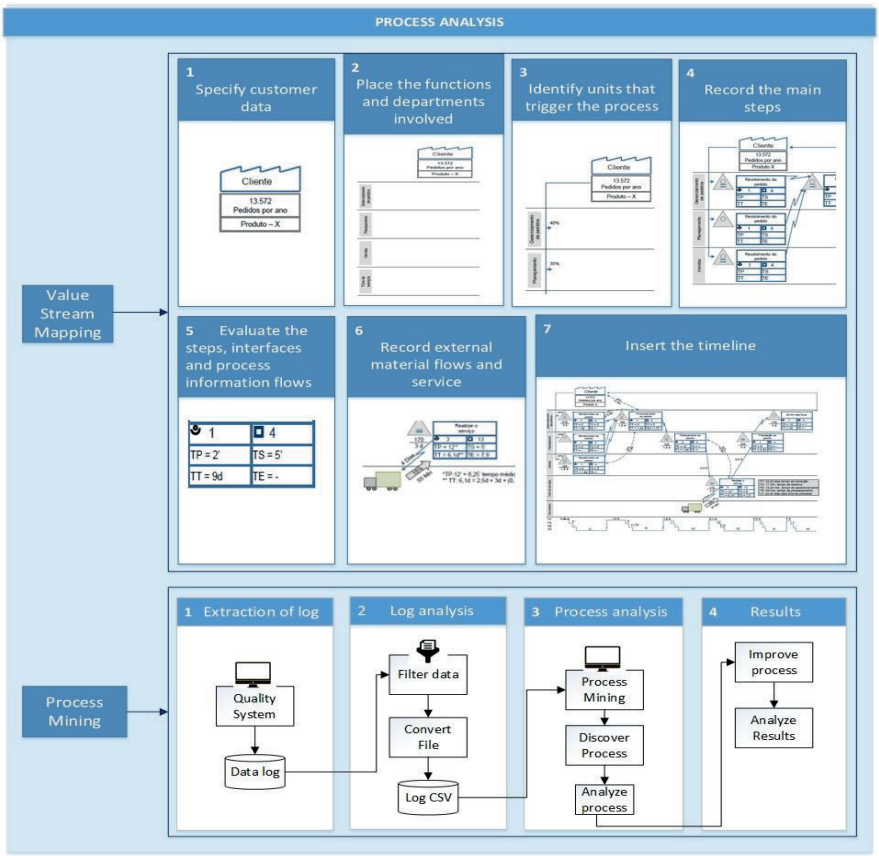

Fig. 1. Methodology

4 Case Study

The company used for the case study is part of the Brazilian automotive sector and has a good level of maturity in lean manufacturing practices. The area to which the methodology is applied is Quality, which has experience in using value stream mapping. In order to increment the VSM with the benefits of process mining, both approaches were conducted. VSM by technicians, Quality engineers, and an external consultant, and the process mining relied on Quality engineering. In both processes, there was also the accompaniment and support of the authors for understanding, applying the proposed method, and analyzing the results.

The execution had two distinct phases. In the first phase, a mapping of the value flow was carried out to handle of non-conformity, using paper and pen. The process was analyzed in-depth following the steps in figure 1, requiring five meetings of 3 hours to map the process. With this activity, it was possible to perceive the flow of the Handling of Non-Conformity (HNC) as well as to see weaknesses in the process.

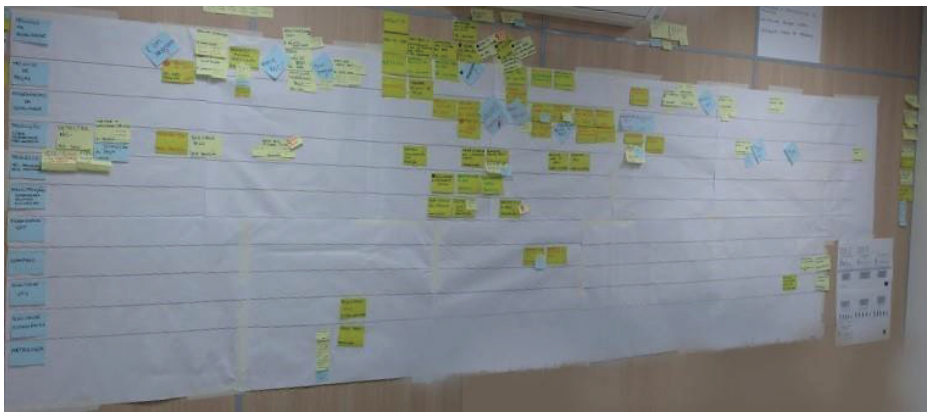

Fig. 2. Value stream mapping (VSM)

In the second phase, with the process modeled by VSM, the focus is on the existing Quality system, and the analysis is done through a log of events that was extracted via the Quality Information System. This step aims to bring the analysis under the lens of process mining in the same process analyzed by VSM, providing an increase in analysis and other possibilities for improvement.

The next subsections of the article detail the application of process mining from log extraction to processing analysis in the software. The results step, shown in Figure 1, does not apply to the scope of this article, since the present study intends to verify what the process mining can add to the VSM. However, with the analysis of the process found, the team responsible for quality management in the company will continue to improve the process and further evaluate it.

4.1 Extraction and Analysis of Log

The structure of the case study follows the methodology presented in Figure 1. It starts with the step of extracting the Quality System data log, and after the data collection, a first sorting was carried out on the file, removing unnecessary information for the study. The file was then converted and mined in the DISCO software, where the process could be analyzed by checking its adherence to the VSM model.

Although process mining is a very important tool for analyzing and understanding a process, the starting point for mining is not always easy. More than extracting data from a system, it is necessary to prepare it for the processing in question. Thus, the first stage needs the support of the IT area to filter the activities and the important attributes for analysis. For the study, the case ID and records such as date, activities, and employees were selected. After identifying the attributes of the log, it was converted to the standard format of the DISCO software.

4.2 Process Analysis

The analysis of the process included 27,181 events, which in turn were contained in 7714 cases, 4 activities, over 13 years and 11 months. The activities of the process are: Opening, Plan in execution, Analysis of effectiveness, and Completed. It is expected to observe that activities follow this order within the process model found by data mining.

Process Discovery

Through the event log, the Software automatically builds a process model, where it is already possible to find out how the process actually behaves, that is, in this case, it could analyze itself from the process flow found if what was mapped in the VSM corresponds to the reality. Process mining, therefore, allows companies to confirm or correct their ideas about the existing process. Besides, the tool allows an in-depth analysis of the process performance.

The Fuzzy Miner algorithm was used to analyze the process model, this algorithm is capable of analyzing models with a large number of events. Figure 3, shows the model of the uncovered process, indicating the real behavior of the handle of the nonconformity process. As can be seen, the process model is a spaghetti model, which contains frequent and infrequent paths. Analyzing the process, we can see that in most cases the events start with plan in execution, skipping the Open stage.

The extracted model showed differences from the proposed ideal model. Taking into account that the model phases are similar to a PDCA, where: Plan is Open, Do corresponds to Plan in execution, Check is the Effectiveness Analysis and finally, Act would be the Completed profile. We have the following situations: (1) most analyzes (6495/7714) start from the plan in execution, not making clear the study and preparation to understand and propose the appropriate action plans for the HNC; (2) 47 analyzes return from the plan in execution to Open, implying that the plans were created and deleted; (3) 56 times was looped in the Open status; (4) The stage of the Plan created for the approval and closing of the same occurs within normality, however,

1737 times the plan is not effective and returns to replan the actions, it can also be understood as the action is taken and the problem to recur; (5) The effectiveness analysis when the analysis is approved receives the status of completed. Some non-compliant flows are also observed, showing great potential for improvement in the system regarding compliance.

In summary, the model did not show the expected behavior, where the handle of non-conformity would start with the Open activity, move to the Plan in execution, after the Analysis of effectiveness, and finally, the handle would be concluded.

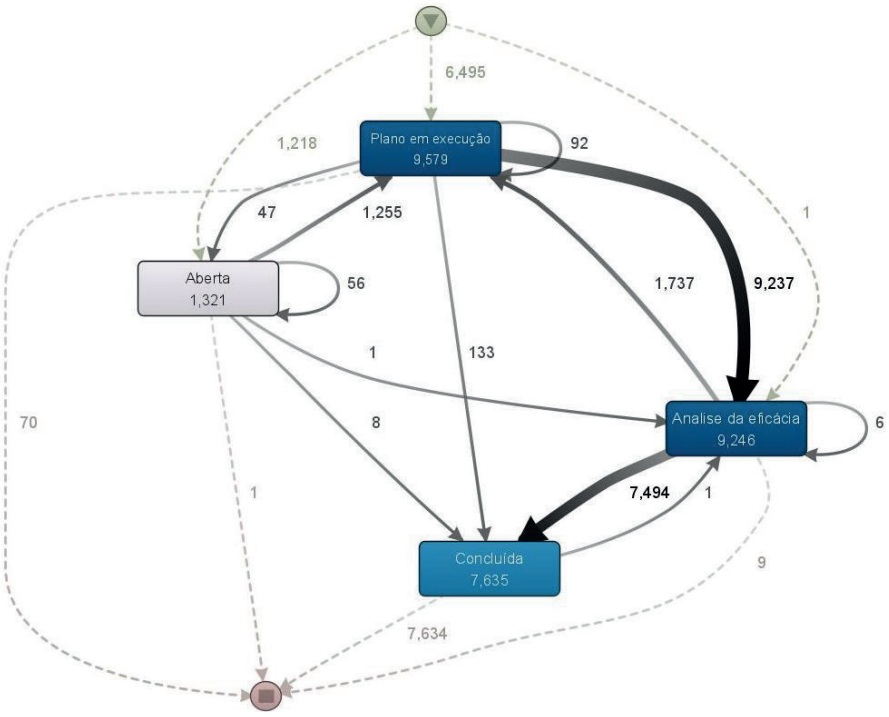

Fig. 3. Model of the non-conformity treatment process using the DISCO software.

Process Performance Analysis.

This section presents the analysis of the performance of the Quality System, which intends to discover the bottleneck of the process and whether the events presented are within the time limit estimated by VSM. It was possible to evaluate the events since when the system was created, for comparison, the average time between events was chosen. Figure 3, shows the performance of the process presented in the log, with the thickness of the arc and the color representing the average times between the activities. The thicker and stronger color indicates the bottleneck of the process. As can be seen in Figure 3, the bottleneck of the process is between the activity of Plan in execution and Analysis of effectiveness with an average of 18 weeks and with 9237 plans created. The 61.8-day effectiveness analysis shows that technicians wait this time to understand what action was effective. The accuracy of the information extracted, the

time used, as well as the ease in analyzing the data, were characteristics evaluated by practitioners as very positive in the use of process mining.

Another analysis made was in relation to the conformity of the process, which showed that of the 7714 events that started, 7635 appear finished. 1737 action plans were not effective, and in the effective analysis, they were not approved, returning to the previous phase to redo the same. One must question the importance of the Open activity, which in most cases starts with the plan being executed. Taking into account that the time taken to handle of non-conformity is aimed at 20 days, it can be seen that in most cases this time is exceeded. For a better analysis of this fact, a filter was applied based on the 20-day estimate for the resolution of the handle of non-conformity, where only the events that are within the time limit were left. As a result, 18% of the events in the log are within the stipulated time limit. Within these cases, the average time between the execution plan activities and the effective analysis was 4.8 days.

5 Discussion

During the realization of the case study, it was observed that the VSM methodology analyzed the current state of the process flow of the handle of non-conformity. The approach aimed to provide the Quality manager with a detailed mapping of activities that involve non-conformities, the human resources used, and the time consumed. In the Quality department, the main reactive activity is the problem-solving process, which includes registering the problem in the Quality system, analyzing the root cause in the Kaizen model (A3 / project), and defining and monitoring the countermeasure. The technicians are responsible for this activity and it was detected that they were overloaded, therefore, the quality of the handling was not as good as expected. VSM was able to identify and eliminate double work and waste from the process, improve performance and the workload can be revised.

However, the work mobilized the entire department with many hours of work to arrive at a photograph of the process. The energy to map the flow was so great that repeating the process with the required frequency proved to be unfeasible. The discussions for the construction of the map were based on people's intuition, which in addition to taking a long time, often generated inaccurate and unreliable data.

To conduct the activities, it was necessary to hire an external consultant, because although the methodology is quite widespread, many doubts arose on how to map the activities and mainly the fact that people often present different, but legitimate points of view. VSM achieved some of its objectives, but for the manager, it was not possible to promote more profound changes because it would be necessary to run the cycle several times, which proved to be impracticable due to the energy and resources used. The comparison of the two VSM and process mining approaches is summarized in Table 2.

In relation to VSM, it is possible to verify that process mining allows a visualization of the process as it actually occurs, thus requiring less human effort and mitigating the subjectivity existing in the discovery phase. In addition, process mining allows

for quick and constant updating of process models, as it occurs from readings, from systems, extracted in real-time and stored in an event log.

Still, to be able to execute process mining projects, there is a need for data storage, requiring computational structure and acquisition systems. These data can be extracted with dirt and found scattered in several different systems, which impacts the need for processing these data. In addition to that, structuring to collect data from systems can imposing the organization with implementation costs.

Table 2. The comparison of approaches: VSM and process mining.

	VSM	Process Mining
Numbers of people involved.	22 – the entire Quality team	2 - 1 engineer and 1 Manager
Hours used	5 meetings of 3h x 10 people = 150 hrs.	To remove the event log from the system: 8 hrs, to pass to the DISCO software: 10hrs, analysis time: 10 hrs = 28 hrs
Level of detail	Relation to people's capacity for abstraction.	Logs written to the system
Ability to repeat the process	Difficult - difficulty in bringing together all involved	Easy - whenever needed
Reliability of information	Estimated times - People have different ways of seeing the process and many disagreements regarding the duration of activities.	Times collected from the system - The data are in accordance with the process performed in the Quality system
Period analyzed	It is a photograph of the process.	It is possible to analyze different moments of the process
Ability to assess system compliance	It's not possible.	It is possible to see all occurrences, even those that have not been completed or that have not followed the required process.

6 Conclusion

This study presents a method for using process mining to increment VSM. In general, processes, such as the non-conformity approach, are dynamic and complex. Thus, the data provided by systems is highly valuable so that, when applied to process mining, and analysis of the real situation of the process is carried out, enabling a deep understanding of the behavior of the activities.

From the evaluation of the contents present in the literature, in addition to the applied case study, it is understood that currently, process mining can be an incremental tool for process improvement initiatives such as VSM. Process Mining allows the discovery and updating of models that are true to reality, supporting the analysis and decision-making phases present in the VSM. Decision making and improvement planning is not carried out by the machines and is not foreseen in mining models. Thus, the models are complementary. In the future, with greater technological maturity and mining models, they can become prognostic, making the model itself propose and set up the improvements, making the process mining complete and enabling the replacement of the VSM.

One of the objectives achieved with the use of the PM after the VSM, from the case study, was to understand the real lead time of the dealings, making it clear that the times before suggested by the people in most cases were very different from what actually happened. It was also possible to prove that many analyzes did not follow the recommended path, and worse than that, many were not even concluded, being lost in the system. It is possible to infer that this incremental approach can extend to other types of processes, as long as the system requirements and event log extraction are met.

According to Slack and Lewis (2009) the excessive "quality bureaucracy" associated with TQM is expensive and time-consuming. This affirmation with the PM was proven with a very high lead time of the negotiations and with the percentage of analyzes that were started and were not finished being lost in the system, characterizing a total waste.

Future work can be developed through event logs containing a greater wealth of details so that the additional information provides an analysis of compliance regarding the stages and times of handle of non-conformity processes, as well as the inclusion of incremental improvements in the process. Also, these works can address other types of processes to validate the proposal developed against new applications.

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Agile DMAIC Cycle: An Approach Based on Process Mining

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Abstract. As a quality improvement methodology, Six Sigma must always be seeking to improve itself, seeking tools that can help to optimize processes and generate value. Identified by the literature, Process Mining has this power, using mining techniques to improve the stages of a Six Sigma process, stages of the DMAIC cycle (Define-Measure-Analyze-Improve-Control). Proposing to unite these applications, this work aims to develop a more efficient DMAIC cycle, in terms of reliability and time, developing the agile DMAIC cycle through an approach for process mining. The aim of this study is to provide a more agile application for Six Sigma, using data from automated processes that are increasingly available, and contribute to the evolution of how continuous improvement projects are currently conducted. To verify the functionality of the agile DMAIC cycle, a case study was performed in a multinational automobile manufacturer, using data from its dealership chain, seeking to identify the main defects of the vehicles. The study is still under development, but the preliminary results are available in this work.

Keywords: Process Mining, DMAIC, Processes Improvement.

1 Introduction

Process improvement is highly dependent on the ability to identify a problem, develop solutions and implement them [7]. There are several methodologies that follows steps starting from the identification of a solution to the implementation a solution, and one of the most used methodologies in the world is the Six Sigma.

With the emergence of Six Sigma in the 1980s, and with its recognition due to several successful cases, the methodology was the most effective to achieve continuous improvement. Over the decades, the Six Sigma methodology has been adopted by many organizations, regardless its size [15].

The Six Sigma encompasses a wide range of statistical methods and quality tools, seeking to reduce eventual quality defects and costs, giving a lot of importance to the statistics of the process, becoming a method focused on measurable results and with a quick conclusion of the project [7].

The research in the process improvement area is something that is always in vogue, and one of the most emerging areas in this type of study is the Process Mining which

aims to discover, monitor and improve processes from data (also known as event logs) obtained from information systems [1]. Process Mining is not a method that replaces more classic methods like Six Sigma itself, however, it can be used to validate and accelerate process improvements [3]. This is what this research proposes, a methodology that intersects six sigma and process mining, using both in a case study that will be presented in one of the topics of this work.

One way that has been shown efficiency to use Process Mining in Six Sigma is to use mining techniques in the DMAIC cycle (method that guides the tools and steps to be proceeding in Six Sigma), with these mining techniques, it is possible to provide a visible agility at the end of the process [9;10]. Although there are already other studies in this area and some concepts from these studies are used in this work, this research has a slightly different view, bringing a new approach to the execution of the DMAIC cycle and validating its concepts in a practical way through a study of case.

This work intends to demonstrate through preliminary results the usability and improvements that can be achieved in the DMAIC cycle when process mining techniques are used. These preliminary results were obtained using the agile DMAIC cycle in logs provided by a multinational automobile manufacturer located in the state of Paraná, Brazil.

2 Contextualizing

2.1 Six Sigma

Developed at Motorola in the mid-1980s, Six Sigma is a methodology with the goal to improve the output results of a process, minimizing variations and eventual defects that may happen [16]. A trained professional leads the project using one of two typical approaches to a Six Sigma project, namely DMADV and DMAIC. DMADV is focused on product development, while DMAIC is focused on process improvement issues. for the purpose of the paper, will be studied the DMAIC approach. Figure 1 illustrates each stage of DMAIC cycle and addresses the crucial points of each.

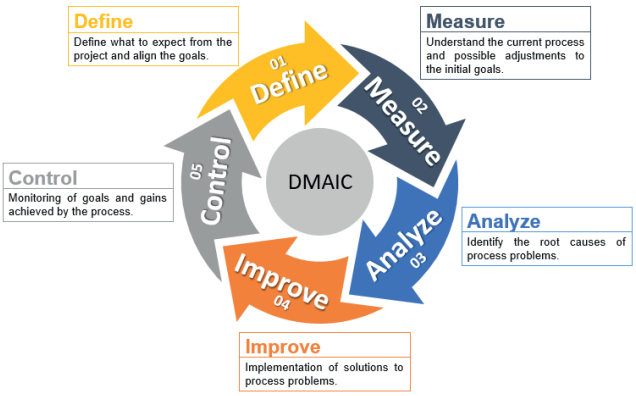


Fig. 1. DMAIC cycle.

The DMAIC cycle is one of the pillars of the success of Six Sigma, it is a structured and sequential method that seeks to emphasize the customer's voice, using tools with statistical basis to seek a better solution. DMAIC is an acronym for Define, Measure, Analyze, Improve and Control. Where each letter corresponds to a stage in the DMAIC cycle [12].

It is necessary to follow the steps in their proper order, each step has its importance and expected results after they are completed, these characteristics are detailed in table 1.

Table 1. The main objectives and expectations of DMAIC cycle. Adapted from [1;6]

Stage	Stage importance?	What is expected at the end of the stage?
Define	Define is where the cycle begins, at this stage the scope of the project is defined, which is vitally important, because a poorly defined or superficial scope can cause the project to fail.	The project team is expected to have the objective well established, ensuring that the project's goals are aligned with those of the company, an estimate of the expected gain after the implemented project, a mapping of the entire macro process involved, and a schedule of the entire DMAIC cycle determining the estimated time for each stage of the cycle.
Measure	Measure is the step where it is possible to understand the current state of the processes and how they work, through the acquisition of indicators.	The project team is expected to have the objective well established, ensuring that the project's goals are aligned with those of the company, an estimate of the expected gain after the implemented project, a mapping of the entire macro process involved, and a schedule of the entire DMAIC cycle determining the estimated time for each stage of the cycle.
Analyze	Analyze aims to identify and select the root causes of project problems, validating through static tools.	It is necessary that the root causes of the priority problems have been identified, so that it is possible to present what is wrong with the process, and how to implement the changes that must be adopted in the next stage of the cycle.
Improve	Improve is where the solutions to the problems of the process are presented, making the necessary improvements, and checking if the specific goals have been achieved.	At the end of Improve, the project team must have made a list of solutions for each problem in the project, an action plan for the implementation of the solutions, made the necessary improvements, and evaluate through the results of the improvements if the goals were really achieved.

Control	Control is necessary to monitor the goals, ensuring that the gains made in the project are maintained.	Concluding the Control, it is expected that the project has generated new processes, well defined and aligned, that the goals have been achieved, that there is a plan to monitor the project periodically, as well as all the documentation and lessons that have been learned throughout the project

2.2 Six Sigma

Process Mining is a rising research field, that incorporates mining techniques that can be used in companies that own a mature database, providing support for process improvements [1].

The basis of Process Mining is the *event logs*, which are event records of a process, these event logs are obtained through information systems that are already available in corporations, the idea of process mining is to discover a process, monitor it, and improve it using appropriate techniques for the logs, in most of the logs it is possible to extract information about the project execution steps and the timestamps, such as when the process starting and completing. The figure 2 shows the methodology proposed by Eck et al. [6] for the execution of a typical process mining project, starting from the planning until the exhibition of results.

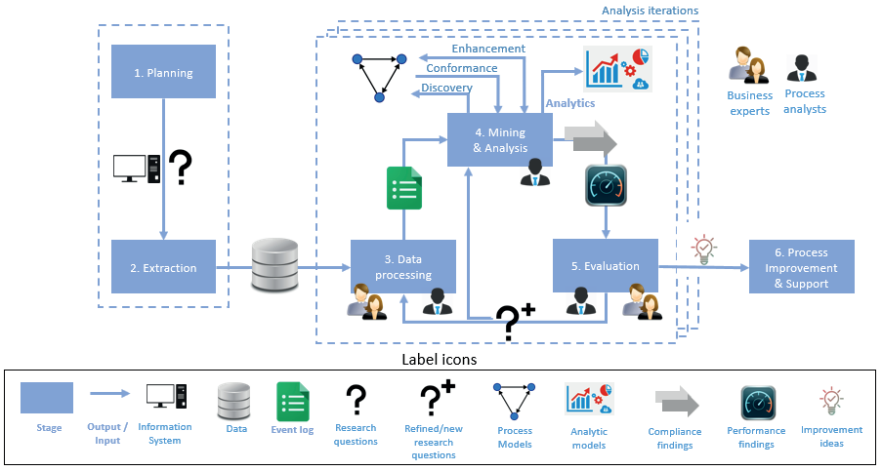
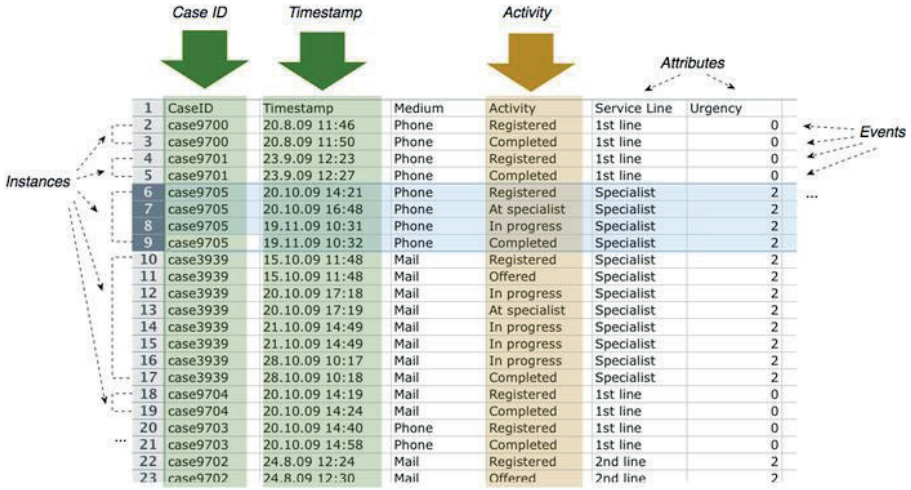


Fig. 2. Process Mining Methodology. [6]

The basis of process mining is the event logs, these logs are data acquired from information systems and are identified in tables, as the figure 3 that illustrates the elements of a log, at least three of these elements are mandatory which are Case ID, Timestamp and Activity. These elements are necessary for the mining software to generate the model that describes the process to be mined.



	CaseID	Timestamp	Medium	Activity	Service Line	Urgency
1	case9700	20.8.09 11:46	Phone	Registered	1st line	0
2	case9700	20.8.09 11:50	Phone	Completed	1st line	0
3	case9701	23.9.09 12:23	Phone	Registered	1st line	0
4	case9701	23.9.09 12:27	Phone	Completed	1st line	0
5	case9705	20.10.09 14:21	Phone	Registered	Specialist	2
6	case9705	20.10.09 16:48	Phone	At specialist	Specialist	2
7	case9705	19.11.09 10:31	Phone	In progress	Specialist	2
8	case9705	19.11.09 10:32	Phone	Completed	Specialist	2
9	case3939	15.10.09 11:48	Mail	Registered	Specialist	2
10	case3939	15.10.09 11:48	Mail	Offered	Specialist	2
11	case3939	20.10.09 17:18	Mail	In progress	Specialist	2
12	case3939	20.10.09 17:19	Mail	At specialist	Specialist	2
13	case3939	21.10.09 14:49	Mail	In progress	Specialist	2
14	case3939	21.10.09 14:49	Mail	In progress	Specialist	2
15	case3939	28.10.09 10:17	Mail	In progress	Specialist	2
16	case3939	28.10.09 10:18	Mail	Completed	Specialist	2
17	case9704	20.10.09 14:19	Mail	Registered	1st line	0
18	case9704	20.10.09 14:24	Mail	Completed	1st line	0
19	case9703	20.10.09 14:40	Phone	Registered	1st line	0
20	case9703	20.10.09 14:58	Phone	Completed	1st line	0
21	case9702	24.8.09 12:24	Mail	Registered	2nd line	2
22	case9702	24.8.09 12:30	Mail	Offered	2nd line	2

Fig. 3. Process mining input data. [8]

Process Mining consists of observing a process activity through its logs and using them in any of the three types of Process Mining, which are *discovery mining*, *conformance mining*, and *enhancement mining* [1;2], these characteristics are detailed in table 2.

Table 2. Types of mining and usability. Adapted from [1;6]

Mining types	Why use this type of mining?
Discovery Mining	From an event log used as input, it is possible to automatically discover (using process mining software) a process model (Petri Net, BPMN, EPC, Causal Network ...). Given this model, it is much easier to understand the process being worked on, saving time and work of having to do a traditional process mapping.
Conformance Mining	In conformance mining you can start from an already established process and with an expected behavior, it is possible to do an exploratory mining in order to detect whether the acquired event log has the expected behavior or if there is any inconsistency. When addressing to process conformance, it is possible to make gains in several areas such as quality, time, resources, and costs.
Enhancement Mining	This type of mining takes in consideration the event logs to drive improvements, based on a process performance analysis. This is a great tool to find possible bottlenecks and deviations from the process.

2.3 Process Mining in DMAIC

Six Sigma, as a quality improvement methodology, cannot remain with a static structure, if it wants to continue generating value [14]. Based on this premise, originated the idea of using another quality tool that could improve the DMAIC cycle. A

systematic review of the literature was carried out in search of something that could add value to this methodology, and it was thought that process mining could be that something from the thinking proposed by Aalst and Dustdar, where which specifies that process mining is not a method that replaces more classic methods of quality, such as Six Sigma itself, but it can be used to validate and accelerate process improvements [3].

Using the digital libraries IEEE Xplore, Google Scholar, SpringerLink and Web of Science. The literature review was made using the key words "Process Mining", "Six Sigma", "DMAIC", "Processes Improvement" and "Data Mining", so that they were combined in the search. This search resulted in 822 relevant publications, and subsequently only 4 of these researches were selected, which drew attention for bringing a process mining application within the DMAIC or notes of possible applications. These researches bring very valuable information regarding the application of these two methodologies together, like how to accelerate the design time, usefulness and possible applications of certain mining techniques in given stages of the DMAIC, usefulness of using real data from logs, and the benefits of a support tool that combines the two methodologies. Table 3 shows these researches and their main contributions.

Table 3. Most relevant research and their contributions.

Research name	Main contributions
Accelerate DMAIC using process mining [9]	After applying process mining techniques in the DMAIC phases it was possible to accelerate a process that would take an average of 9 to 12 weeks for an average duration of 4 to 6 weeks.
Data perspective of lean six sigma in industry 4.0 [5]	It was interpreted that the discovery techniques are useful for the define and analyze phases, in addition to that the Conformance techniques are applicable in the Measure and Control phases.
The future of continuous improvement [11]	It was understood that using real data from the event logs in the define phase would help to define the scope of the project, and with process mining techniques the measure and analyze phases would be streamlined, highlighting also that in the control phase it would be very useful to use process mining to assist the daily management of operations.
Process Mining for Six Sigma [10]	In order to fill a gap in a study dedicated exclusively how bridging the gap between Six Sigma and Process Mining, was developed the PMSS (Process Mining for Six Sigma), providing guidance on how to use mining techniques within the DMAIC cycle.

Taking advantage of all this shared information from these previous researches, the concept of the Agile DMAIC cycle began, bringing in a more specific way a direct application of process mining within the DMAIC cycle.

3 Agile DMAIC Cycle

The core of this research is to generate a model in which it can be followed to be applied in continuous improvement projects. Aiming as a final product a structured method for consultancy in Six Sigma projects, called Agile DMAIC Cycle.

Focusing on the approach of incorporating Process Mining along with the DMAIC cycle, without changing the progress of a standard Six Sigma project, the agile DMAIC cycle has as its main advantage the execution time, reducing the time spent in the initial stages.

Currently, this study has been limited only to discovery mining, having only direct influence in the Define, Measure and Analyze stages. However, the natural way is that the research continues to evolve and, in the future, also influences the stages of Improvement and Control, through the others mining techniques.

The Agile DMAIC Cycle has 8 phases that occur over the five stages of the classic cycle. The figure 4 shows the flow of the Agile DMAIC Cycle, as well as determinates which professionals are involved in which phases.

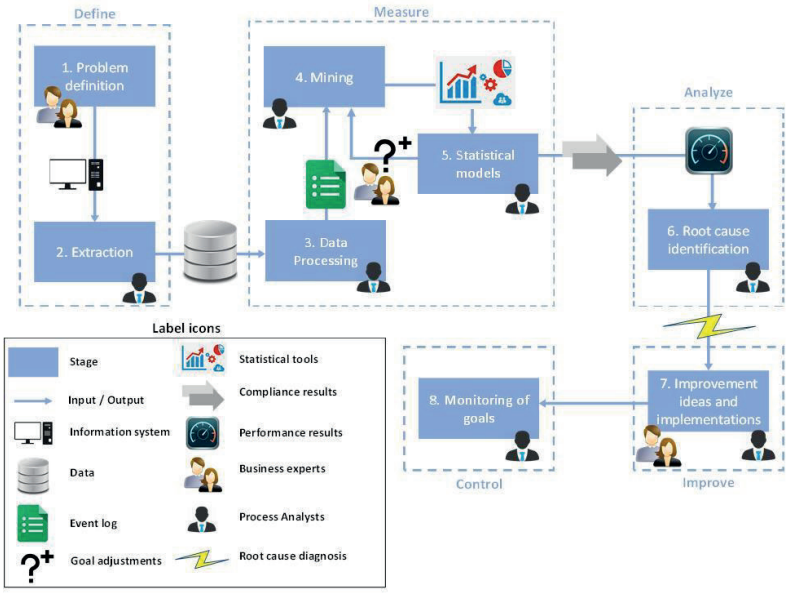


Fig. 4. Agile DMAIC Cycle methodology.

Stage 1 - In this stage, the business specialists define the problem they want to focus their efforts on solving, defining the scope and goals of the project.
Stage 2 - In this stage, data extraction occurs, process analysts based on the defined problem, analyze which information systems they could use to acquire data from the process, and make the necessary data extractions.
Stage 3 - In the Data processing stage, data is cleaned, generating event logs that can be used in mining software.

Stage 4 - This is the stage where the logs are updated in the software, generating the mapping of the process, and applying mining techniques, to obtain the statistics of the events.
Stage 5 - The statistics generated are used in this stage for the design of static models, which together with business specialists are evaluated if it is possible to reach the initial goal or if it is necessary to make any adjustments.
Stage 6 - This is the stage where the root cause of the problem is investigated, supported by statistical models, looking for variations and possible bottlenecks, generating a diagnosis with these causes.
Stage 7 - Based on the diagnosis, this stage explores the possible solutions to the problem, followed by an action plan, and the appropriate implementations.
Stage 8 - The stage that ends the cycle, is responsible for ensuring that the gains obtained with the project are maintained over time, creating a plan for monitoring the process after the project is concluded.

4 A case study and preliminary results

Proposing to test and validate the Agile DMAIC Cycle, the methodology has been applied in a case study, at the time this article was written the project is still running, however due to the evolution of the study already in this state of application, it was considered that it would be positive to expose the preliminary results of the methodology. The case study was based on data provided by a multinational automobile manufacturer located in the state of Paraná, Brazil.

4.1 The problem

The company would like to understand the main causes of the defects of its vehicles, for that they wished to make an exploratory study aiming to identify the main types of defects by models of vehicles. Subsequently intending to understand root causes, take mitigation measures, prioritizing the most significant actions first.

For this study, the company made available logs of its car dealerships chain, where from the chassis number, it is possible to identify the events and dates of these events that occur in a vehicle. These logs also have problem codes (used by the company), how many kilometers a vehicle has on a repair order and the model of the car.

The possible occurrences are vehicle manufactured, BVM registration, vehicle delivered, BIM registration, vehicle sold, and repair order. BIM and BVM registration will not be considered since they are internal company registers, and they do not have influence on the process. The information available for analysis are as follow:

i) Vehicle manufacturing is the event where the vehicle manufacturing is completed.
ii) Vehicle delivered is the event in which the vehicle is delivered from the factory to the car dealership.
iii) Vehicle sold is the event in which the vehicle is delivered to the customer.

iv) Repair order is when a technician identifies a problem and generates a repair order.

The figure 5 is an example of a log, the chassis number has been blurred due to the privacy of company data.

Chassis number	Event date	Event	Problem code	Km	Model
[redacted]	01/12/2017	Vehicle Manufactured			
[redacted]	13/01/2017	BVM Registration			
[redacted]	04/07/2018	Vehicle Delivered			
[redacted]	08/06/2019	BIM Registration			
[redacted]	15/08/2019	Vehicle Sold			
[redacted]	31/07/2019	Repair Order	GSFA-V01-CAR BODY	40462	E5
[redacted]	08/12/2019	Repair Order	GSFA-V13- INTERIOR TRIMS	41102	E5
[redacted]	08/12/2019	Repair Order	GSFA-P15-SAFETY SYSTEMS	41102	E5
[redacted]	01/08/2020	Repair Order	GSFA-V14-SEATS	48707	E5
[redacted]	01/08/2020	Repair Order	GSFA-V14-SEATS	48707	E5

Fig. 5. Event log example.

4.2 The procedure

The procedure followed in the project was as described in figure 4, where the same flow was followed and executing the steps determined within each stage of the DMAIC cycle.

4.2.1 Define

Problem definition (Stage 1): The quality sector of the company has for some time seen a high rate of defects in its vehicles, but these defects are not directly reported to this sector or to the administrative sector. These complaints and defect identifications come through the customer complaints from the car dealership chain where customers purchased their vehicles. In order to carry out an exploratory study to identify the main defects of its vehicles, the problem of the project was defined, the identification of the models that concentrate the highest number of problems, and from them prioritize the mitigation of them for each of these models, obtaining an overview of defects and already having an improvement model in progress. It was defined that the information system that could provide the data for the project would be the system of repair order registers, which the car dealership uses. This decision-making came from Business Experts.

Extraction (Stage 2): At this stage, one of the quality sector analysts extracted the data from one car dealerships, in which he judged that he would have data mature enough and that would generate a good sample.

In the extraction stage, it is intended to acquire information registered in information systems. The extracted data had a direct influence on the scope of the project, which was defined in the previous step. Searching for defects reported by customers, where in addition to defining what data would be extracted, the period to be extracted was determined. As previously stated, the data is provided by a car dealership chain, in which a .csv file was generated with the necessary information to be used in the mining

software. Figure 6 shows an example of a post-extraction log excerpt, where there is more information than is necessary for mining and that has not been used, there is no need or utility in the Damage and Customer description of the problem columns for mining, due to being non-standardized and subjective fields, the damage field is what the technician responsible for the assessment notes the identified problems in his own way and the *Customer description of the problem* field are the words of the customer to describe the problem. These two fields, besides not being standardized, make it difficult to understand for the software, they are fields that are suppressed by Problem Code, which is the code used to report the identified problems.

Chassis number	...	Event	Damage	Problem code	Customer description of the problem	KM	Model
[redacted]	...	Vehicle Manufactured					
[redacted]	...	BVM Registration					
[redacted]	...	Vehicle Delivered					
[redacted]	...	BIM Registration					
[redacted]	...	Vehicle Sold					
[redacted]	...	Repair Order	LACK OF BACK LEFT DOOR PLASTIC FILM ADHERENCE	GSFA-V07-EXTERIOR ACCESSORIES	LEFT BACK DOOR BAND TAKING OFF	42002	A1
[redacted]	...	Repair Order	LACK OF ADHERENCE; DECORATIVE BAND OF THE LEFT FRONT DOOR; UNPLUGGING	GSFA-V07-EXTERIOR ACCESSORIES	LEFT FRONT DOOR BAND TAKING OFF	42002	A1
[redacted]	...	Repair Order	LACK OF ADHESION OF THE DECORATIVE BAND DOOR FRONT RIGHT; UNPLUGGING	GSFA-V07-EXTERIOR ACCESSORIES	RIGHT FRONT DOOR BAND TAKING OFF	42002	A1
[redacted]	...	Repair Order	UNLOCKING; FRONT SEAT BELT LIMIT BUTTON LEFT; EXTRAVING	GSFA-P15-SAFETY SYSTEMS	LEFT BACK BELT BUTTON FELL	42002	A1

Fig. 6. Log post-extraction.

4.2.2 Measure

Data processing (Stage 3): The data received are prepared to become event logs, they are parameterized to a format that can be processed in the mining software, often the data comes with more information than is necessary, and which would not be relevant for the analysis, so in this step it is also defined which data has relevance, already thinking about which attributes such as case ID, activity, timestamp, resource or other relevant attribute. In the result, is expected certain similarity to the figure 5.
Mining (Stage 4): The event logs are imported into the mining software, in this project the software used was DISCO by Fluxicon, where it is necessary to identify the columns as Case, Activity, Timestamp, Resource or other. After importing the event logs, the software generated a process map. In figure 7 on the left side in blue is the process map in relation to the frequency of occurrences, considering the absolute frequency. Through the process map it is possible to identify that 33449 vehicles were registered

in the information system, and that there were 46463 repair orders, in which 11171 vehicles had more than one repair order. Still in Figure 7 on the right side in red is the process map in relation to the performance of events, considering the median duration.

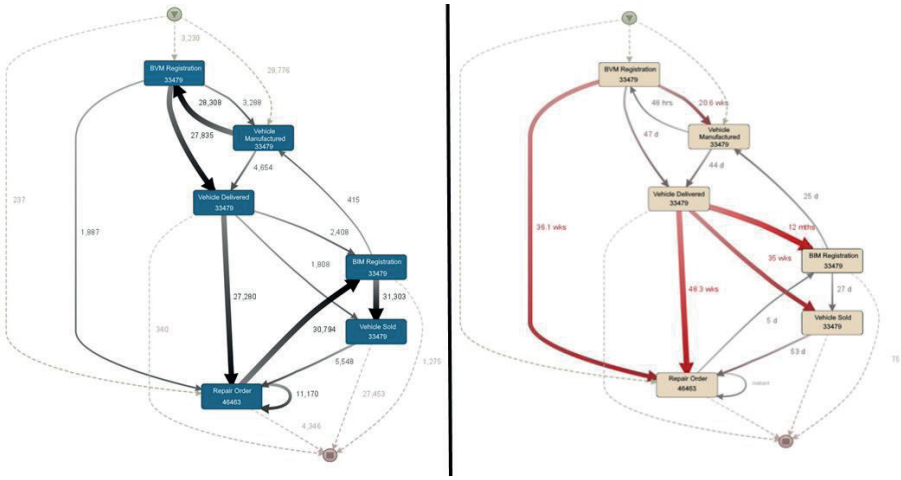


Fig. 7. Process maps.

Figure 8 shows that by the statistics generated on software Disco, within the attributes of the vehicle model and problem code, it is possible to identify that there are 57 problem codes and 10 vehicle models, which have been registered in the system. The figure shows that there is a predominance of the A1 model, being responsible for more than 60% of the repair orders, in the problem code it is also possible to have an idea of what are the most constant problems.

Problem Code
Other attribute

All values (57) | First in case (57) | Last in case (56)

Value	Frequency	Relative frequency
GSFA-S22-PEDAL - PARKING BRAKE - JACK	6,808	14.65 %
GSFA-M07-LOWER BASE ENGINE - CLUTCH	4,151	8.93 %
GSFA-P05-ACCESS - VEHICLE PROTECTION	3,301	7.1 %
GSFA-V14-SEATS	3,121	6.72 %
GSFA-V07-EXTERIOR ACCESSORIES	2,446	5.26 %
GSFA-S34-SUSPENSIONS - FILTRATION	2,096	4.51 %
GSFA-V03-SEALING	2,018	4.34 %
GSFA-P11-AIR CONDITIONNING	1,701	3.66 %
GSFA-M05-CYL. BOCK- ENGINE COVERS - BR...	1,690	3.64 %
GSFA-P20-COOLING	1,548	3.33 %
GSFA-V10-DASHBOARD	1,466	3.16 %
GSFA-P21-FUEL CIRCUIT	1,364	2.94 %
GSFA-V04-MANEUVER OPENING PANEL	1,205	2.59 %

Model
Other attribute

All values (10) | First in case (10) | Last in case (10)

Value	Frequency	Relative frequency
A1	28,938	62.28 %
B2	5,429	11.68 %
C3	4,543	9.78 %
D4	2,919	6.28 %
E5	2,891	6.22 %
F6	1,199	2.58 %
G7	331	0.71 %
H8	164	0.35 %
I9	27	0.06 %
J10	22	0.05 %

Fig. 8. Problem code and Model frequency.

Using the Disco filter tools, the three models that had the most defects were isolated, together these three models represent more than 82% of the total defects, after being

isolated, new event logs were generated. Filters were also used to measure changes in kilometer attributes and the time it takes between the sale of a vehicle and a repair order.
Statistical Models (Stage 5): From the event logs provided in the previous step, pareto diagrams were generated to better understand the distribution of defects in the A1, B2 and C3 models, which have shown the most defects, figure 10 shows these diagrams. In the A1 model the most constant defect is the code GSFA-S22 (22.4%) followed by GSFA-M07 (13.3%) and GSFA-P05 (9.06%). In the B2 model, the defect that most occurred was GSFA-V14 (14.81%), in second and third, two defect codes have a very close value, GSFA-P11 (8.09%) and GSFA-V04 (8.05%). In this model the defects are more distributed than in the A1 model. The diagram of the model C3, which is the third most defective model, the most frequent problem code is GSFA-V14 (19.46%), significantly below the codes GSFA-M06 (7.48%) and GSFA-V01 (5.35%).

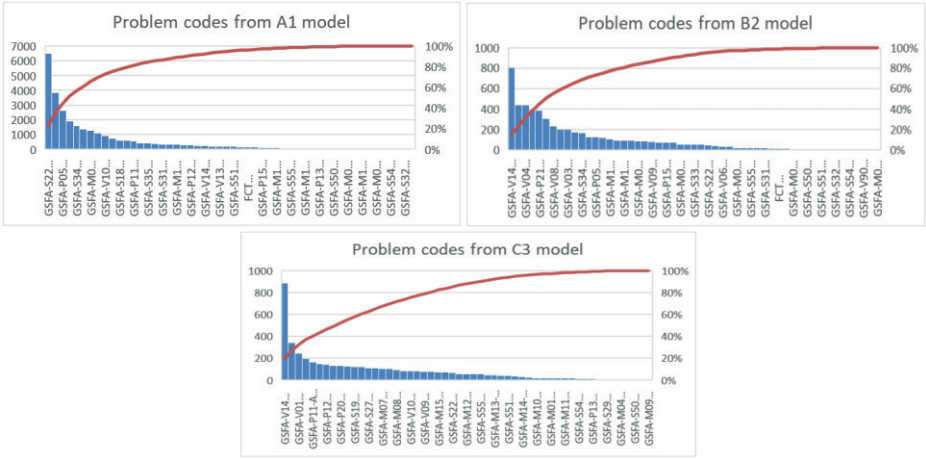


Fig. 10. Problem codes distribution.

An analysis was made focused on the following topics:

i) The time it takes a sold vehicle to return to the dealership.
ii) Repair needed, which may be a first repair order or a second repair order.
iii) Vehicle has already been previously repaired.

The analysis revealed that in both cases the defects mostly occur before completing one year. The analysis carried out was the number of kilometers traveled by the vehicle when a repair order was made, the histogram in figure 12 shows the kilometer ranges and the number of repair orders that were made, in each range. Through this histogram it is possible to reinforce the analysis of the boxplot in which the defects are occurring in the first months of use, due to the defects being more concentrated in low kilometers traveled.

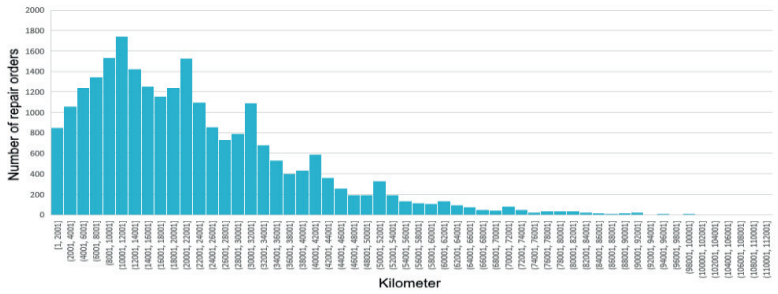


Fig. 12. Kilometers traveled on repair orders.

Also focusing on the kilometers traveled in which a repair order is initiated, an analysis was performed using a filter to isolate the problem codes in a certain time range, as the oldest repair order date is January 2019 and the data were extracted in January 2020, it was considered for analysis to divide the time range into semesters of 2019, 2020 was not considered because it has a very small sample. First, the two defect codes with the highest occurrences were analyzed, namely the GSFA-S22 and GSFA-M07, together representing more than 23% of the total defects. Figure 13 show the first and second semesters of the GSFA-S22 defect. In the first semester, this defect had 1314 occurrences, with the highest incidence between 7412Km and 11111Km.

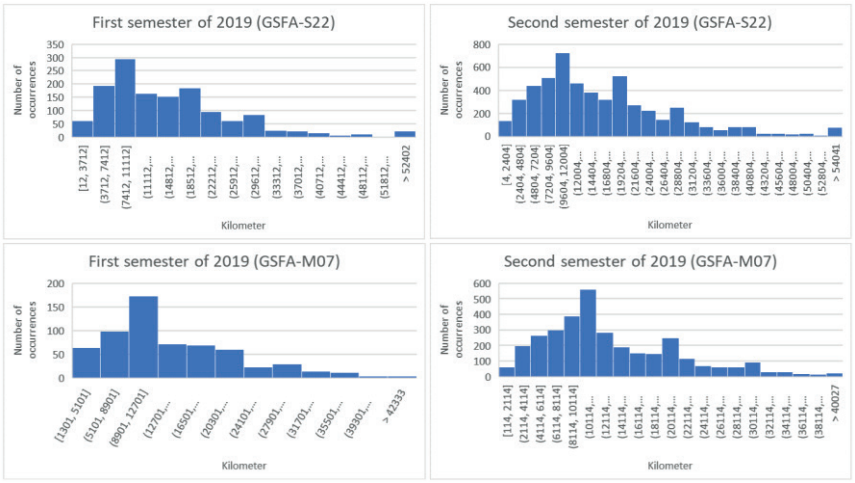


Fig. 13. Kilometers traveled in the repair order for model in the semesters.

In the second semester the defect code GSFA-S22 increased from 1314 occurrences to 5313 occurrences, an increase of just over 400%, in addition to the visible increase it is possible to notice that the apex of the problem occurred in a higher number of kilometers traveled.

Analyzing the defect code GSFA-M07, 627 occurrences were found in the first semester of 2019, with a higher incidence between 8901Km and 12701Km. As the figure 13 illustrates. In the second semester of the year, the GSFA-M07 defect code increased from 627 occurrences to 3304 occurrences, an increase of just over 520%, and as in the case of the GSFA-S22 defect, the peak of greatest occurrences was in a higher number of kilometers traveled.

The results were presented to the responsible sector of the company, who found the problems notes very consistent, and believe that what was analyzed about the problems reflect well what they experience in their daily work. It was not necessary to make any adjustment of goals, since the experts consulted gave the guarantee that the path followed was correct, and the initial goal of finding the main defects and solving them seems to be practicable. The increase in the second semester of the two main problem codes will guide the next step, Analyze, with the objective of identifying the root causes of this huge increase in the number of defects.

4.2.3 Analyze, Improve and Control

The next step would be to enter in the Analyze with the stage *Root cause identification* (stage 6), looking for the root causes, that is currently being done, however, as stated earlier, the project is still in progress and there are no consistent results to be presented about this stage at this moment.

The Improvement step is not yet intended to use process mining techniques in the Improvement ideas and implementation step (stage 7). Classic Six Sigma tools will be used, such as Poka-Yokes, Ishikawa diagram, decision matrix and brainstorm.

Control is the step in which it is intended to guarantee the functionality and stability of the improvements. This work intends to test some process mining techniques of Conformance, to ensure that these improvements continue over time.

5 Conclusion and final considerations

This work through theoretical concepts and gaps mentioned in previous studies [5; 9; 10; 11; 14], brought a contribution to a new practical approach to Six Sigma projects, aiming to bring more accurate indicators and a more agile DMAIC cycle.

Presenting encouraging and satisfactory preliminary results, the agile DMAIC cycle has shown capability in bringing a new perspective on process improvement, other case studies will be carried out in the future. At the end of this study, a new systematic methodology is expected, using process mining to make Six Sigma projects more robust.

This work continues in progress and evolution, and in this way, it is also expanding, seeking to improve Six Sigma tools together with mining techniques, just as they were already done in the Define and Measure stages of this work. As was explored in table 3, there are researches that bring the possibility of using the other process mining techniques, further of the discovery mining, the natural path of this research is to include Conformance Mining and Enhancement Mining in the Analyze, Improvement and Control steps. Conformance techniques are applicable in the Measure and Control phases

[5] and it would be very useful to use process mining to assist the daily management of operations in Control phase [11].

Despite the applicability of process mining in other process improvement methodologies, it is important to mention that the task of extracting data can be very complex [4]. The data may not be easily located and may generate logs that are not complete [13]. About data quality, although this did not happen in the case study of this work, it was evident that to succeed the process mining needs a very mature database, the higher the level of data maturity of a company, the better it is the quality of logs that can be generated. In the long term, investing in a greater discretization of data is very advantageous due to the low cost of process mining in relation to traditional projects to acquire this data.

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Environmental impact assessment of industries through a multicriteria decision-making analysis

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Abstract: Activities carried out by industries generate wastes which become a potential risk if there are not properly treated and well-disposed in the environment. More than two hundred industries located in the Province of Salta have been previously classified in twenty categories according to the type of product they made. However, the environmental impact of these industries is still unknown. Multicriteria decision-making analysis (MCDA) are useful methodologies to apply in this cases as they allow choosing the best from diverse alternatives based on multiple criteria, to finally make a smart decision. The aim of this work was to apply a MCDA to identify which categories of industries impact the most on the environment. The Analytical Hierarchical Process (AHP) was the MCDA selected. The alternatives were twenty categories of industries. Five criteria and sub-criteria (shown in parenthesis) were defined: 1- environmental resources (water, soil and air); 2- types of waste (physical, chemical and biological); 3- water consumption; 4- industries features (amount and size); 5- population index. AHP was solved with Expert Choice 11 Inc. Environmental resources and types of waste, were the criteria that weighed the most. Agroindustry was the alternative that impact most on the environment, due to the use of agrochemicals, emission of toxic gases and manure. In second place was the food industry which generates a variety of waste. These results will be useful on decision-making as they allow identifying the categories of industries that most impact in the environment, to propose alternatives for a better waste management.

Keywords: industrial waste, environmental impact, multicriteria decision-making analysis

Activities carried out by industries are source of different types of physical, chemical and/or biological waste, which after their treatment (or not), are usually disposed in the environment, causing sometimes, not only problems in water, soil and/or air but also on people health. The great amount of industries located in a certain area and the variety of activities carried out by them, difficult the identification of each kind of waste generated and their potential impact. Thereby, environmental surveillance organisms that control treatment and final disposal of industrial waste, need appropriate tools for the supervision and control to make better decisions towards a cleaner production. Multicriteria decision analysis (MCDA) are useful methodologies which provide a scientific decision framework for environmental management, where stakeholders participation is as important as economics, environmental impacts,

safety, health and risk, which cannot be condensed into a monetary expression. The purpose of MCDA is to choose the best from diverse alternatives based on multiple criteria. In a previous research [1] a survey was carried out in the Province of Salta (northwest Argentina) regarding industries. It was found that the Province had in that moment, more than two hundred industries spread over fifteen out of twenty-three departments. These industries were classified in twenty different categories according to the type of product made. However, the environmental impact of these industries is still unknown. The aim of this work was to apply a multicriteria methodology to assess which categories of industries that belong to the Province of Salta impact the most on the environment, related mainly to the waste generated.

The analytical hierarchical process (AHP) developed by Saaty was selected as a MCDA [2]. The purpose of AHP is to choose the best alternative among those based on multiple criteria, which are compared in pairwise (X is more important than Y). These criteria are given in an intuitive way and are based on judgments made by experts for priority scales. Saaty provides a consistent way to make such comparisons in a set of numbers representing the relative priority of each of them over another. In general, the judgments made by experts can be inconsistent and detecting the inconsistency is one of the functions of AHP (If inconsistency index is less than 0.1 is acceptable). At the end, each score is combined with the weights of each criterion to produce an overall score (Utility or objective function) for each alternative. In this work, AHP was modeled and solved using Expert Choice 11 Inc software. This decision model includes the following steps: structuring model, introduction of alternatives and prioritization of the elements of the hierarchy and sensitivity analysis.

In this case, the objective function established was to find the categories of industries in the Province of Salta that impact the most on the environment. The alternatives were twenty industries classified according to the product they made: agroindustry, food, automotive, construction, tannery, electric power, industrial equipment, slaughter, graphics, logistics, wood, leather, metallurgical, mining, petrochemical, chemical, service, tobacco, textile and treatment. Five criteria, some of them with sub-criteria (shown in parenthesis) were defined: 1- type of waste (physical, chemical and biological): chemical or biological waste was considered more harmful to the environment than a physical one; 2- environmental resources (water, soil and air): according to the industrial activities, the waste generated may impact on the resources in different ways; 3- water consumption: while greater amount of water is consumed, more effluents will be generated and thrown into the environment; 4- industries features (amount and size): considers that while more industries and larger they are, greater is the amount and types of waste dumped; and 5- population index was defined [1], which considered the number of inhabitants in the area where the different industries are located.

Results showed that type of waste and environmental resources were the two criteria that most weighed regarding the main objective defined (40%, Fig. 1). In the third place and with the same importance were the rest of the criteria: water consumption, industries features and population index (Fig. 1).

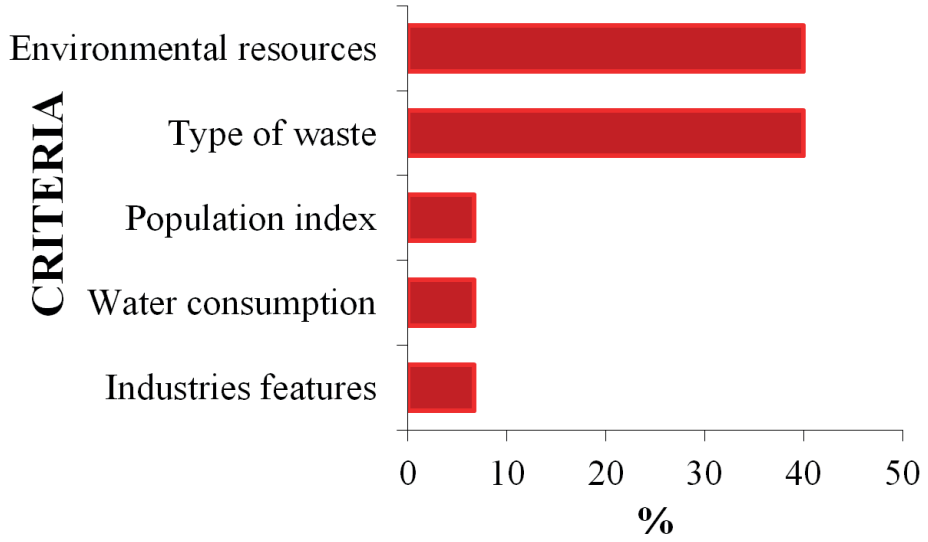

Fig. 1. Weight values (in percentage) of each of the five criteria defined to determine the categories of industries that represent the greatest impact on the environment.

Regarding categories of industries, the agroindustry seems to be the one which impacted the most on the environment (Fig. 2). This is due to the great use of agrochemicals (chemical waste) that have a highly negative impact on the soil and also can be transferred by runoff to waterbodies, causing the contamination of large volumes of water. On the other hand, this type of industry considers livestock farming, whose main waste is due to dry and/or wet manure, which can cause problems in the soil and water bodies, as well as the emission of toxic gases into the air. In this sense, the impact related to the emission of methane gas due to enteric fermentation of ruminants and soil degradation due to overgrazing were also important.

The food industry was the alternative located in the second place, which includes activities such as production of alcoholic and non-alcoholic beverages, dairy (yogurt, butter, pasteurized milk), various packaged foods (candies, cookies, potato chips), etc. All these activities include a wide variety of waste, which can range from effluents with high organic load, as in the case of the dairy industries, to dangerous goods.

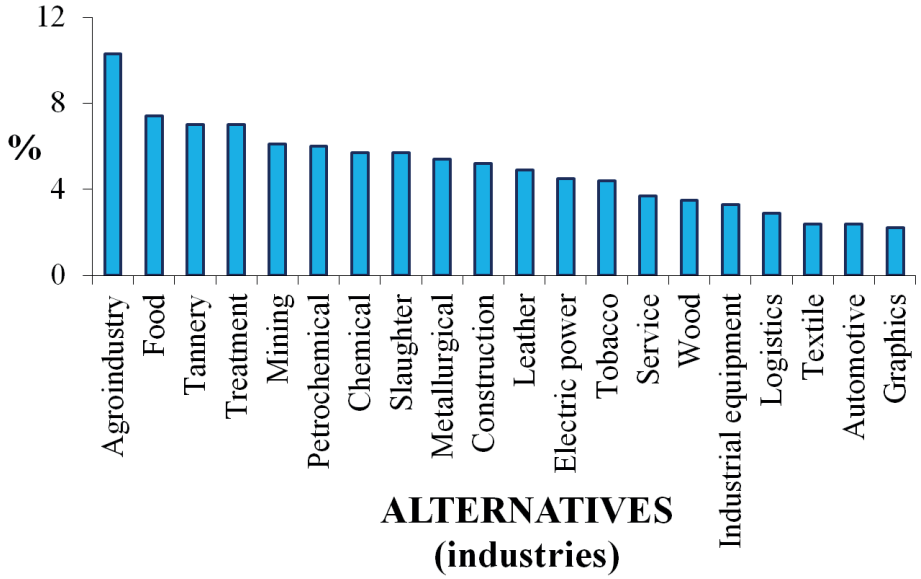

Fig. 2. Objective function values (in percentage) of each of the twenty industrial items analyzed (alternatives) that represent the greatest environmental impact.

The AHP methodology is a robust tool for decision-making. Its application allowed determining the categories of industries where changes should be made towards a better waste management and the development of sustainable industrial activity for the environment and society.

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Exact resolution of the Vehicle Routing Problem with Flexible Time Windows

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Abstract. This article presents an exact resolution of the Vehicle Routing Problem with heterogeneous fleet and flexible time windows. This problem variant extend the classical formulation by considering extended time windows for attending clients, accounting for a more realistic setting in nowadays scenarios. The proposed approach is based on a linear programming formulation implemented in CPLEX. Accurate results are reported: the proposed model is able to solve in reasonable execution times 146 out of 148 problem instances built using data from benchmarks in the related literature (16 to optimality and other 23 with lower cost than for the non-flexible problem variant).

Keywords: vehicle routing, flexible time windows, exact method, CPLEX

1 Introduction

Vehicle routing is a classical area in optimization, with many application in several domains. Vehicle Routing Problem (VRP) is a generic name given to a class of problems with the purpose of determining a set of routes for a fleet of vehicles based at one or several depots, to visit a number of geographically dispersed clients. The main goal of the VRP is to deliver the clients with known demands on the minimum cost vehicle routes originating and ending at a depot [6].

VRP is among the most studied combinatorial optimization problems in operations research. Unlike other traditional combinatorial problems, like the the Traveling Salesman Problem (TSP), where exact solvers can be applied to optimally solve instances with thousand of clients, the VRP is intrinsically more complex, as instances with more than one hundred clients can be hard to solve [1].

This article focuses on a specific variant of the VRP that considers flexible time windows for attending (i.e., delivering goods) to clients. Flexibility on the end of the time windows are included, but considering a penalization of the total cost of the route. This assumption accounts for a more realistic setting in nowadays scenarios, where it would be preferable for the decision maker to use few vehicles to complete a set of routes, even considering that a penalization must be paid for late arrivals in certain clients.

In this line of work, this article presents an exact approach for solving the VRP with heterogeneous fleet and flexible time windows. The proposed approach is based on a linear programming formulation accounting for all the relevant features of the problem, implemented in CPLEX. Realistic problem instances are solved in the experimental evaluation, built by extending existing VRP benchmarks from literature.

Accurate results are reported for the proposed model. The exact resolution approach is able to solve 146 out of 148 problem instances built using data from benchmarks in the related literature in reasonable execution times. Furthermore, 16 problem instances are solved to optimality, and other 23 solutions have lower cost than for the non-flexible problem variant.

The rest of the article is structured as follows. Section 2 describes the addressed problem and its mathematical formulation. Section 3 describes the algorithmic approach to solve the problem using CPLEX. Section 4 reports the experimental evaluation on standard scenarios and problem instances. Finally, Section 5 presents the conclusions and formulate the main lines for future work.

2 The Vehicle Routing Problem with Heterogeneous Fleet and Flexible Time Windows

This section describes the addressed problem and its mathematical formulation.

2.1 Problem description

The proposed problem is a variant of the VRP with time windows considering heterogeneous vehicles, as defined by Jiang et al. [5]. However, a relaxation of the former problem is addressed, since flexible time windows are considered. In the proposed model, early arrivals are only penalized in the waiting time, while late arrivals are allowed within a certain tolerance, suffering a penalty for the extra time that impacts the total cost of the solution included in the objective function. The elasticity given by the flexible time windows allows computing different routes accounting for different attention times withing the tolerance for each client.

The problem model differs from previous proposals since in the VRP with time windows, each client has an associated time window that is defined by the earliest and latest time in which the client is operational. The depot can also have an associated time window that defines the planning horizon for the problem. Previous models have considered that time windows can be of the "hard" or "soft" type. In the case of hard time windows, a vehicle cannot arrive before the earliest time to a client. In turn, soft time windows allow a vehicle to arrive earlier than the time window starts, but the vehicle must wait until the client is operational; however, a vehicle is not allowed to reach the client after the end of the time in which it is operative. In the case of soft type time windows considered in the proposed problem model, violations of the latest time for delivery defined by the time window are allowed, with a penalty in the objective function.

The proposed formulation is detailed in the next subsection.

2.2 Mathematical Formulation

The exact resolution of the problem is based on the linear programming formulation defined next.

The problem is defined on a complete graph $G(V, A)$, where:

- $V = \{0, 1, ..., n\}$ is the set of nodes. Node 0 represents the deposit, while nodes $N = \{1, ..., n\}$ represent the clients.
- $A = \{(i, j) : 0 \leq i, j \leq n, i \neq j\}$ is the set of edges that represent the connections between the nodes.
- t_{ij} is the travel time associated with arc (i, j).

All clients must be visited and for each client i ($i \in N$) the following information is known:

- d_i is the fixed demand of client i.
- s_i represents the service time consumed by a vehicle when servicing the client i.
- $[e_i, l_i]$ is the time window (earliest and latest respectively) of client i. The time windows are of the "soft" type (the vehicle that reaches the client after the end of its time window is penalized).
- ot_i is the "overtime" (tolerance time after the end of its time window) allowed in client i. It is calculated as $ot_i = (l_i - e_i) \times \omega$, with $0 \leq \omega \leq 1$ being a known constant. Therefore, for each client i a new extended time window is obtained, of the form $[e_i, l_i + ot_i]$. The vehicle is penalized if it reaches the client in the margin $[l_i, l_i + ot_i]$.

Regarding the deposit, it is known that:

- $[e_0, l_0] = [E, L]$ is the time window of the deposit.
- $d_0 = s_0 = 0$ since there is no demand or service time in the deposit.

The set of vehicles is modeled as $K = \{1, ..., k\}$, C represents the set of vehicle types and S_c is the set of vehicles of type c inC . For each vehicle of type $c \in C$, it is known:

- q_c is the capacity of a vehicle of type $c \in C$.
- f_c is the fixed cost of a vehicle of type $c \in C$.
- α_c is the variable cost of a vehicle of type $c \in C$.
- n_c is the number of available vehicles of type $c \in C$.

The decision variables are:

- x_{ij}^k: takes value 1 if vehicle k passes through the edge (i, j) and takes value 0 otherwise.
- a_{ik}: time of arrival of vehicle k to client i.
- o_{ik}: amount of time that the vehicle k exceeds the time range of the client i (it is called "overtime" of vehicle k in the client i").

Finally, other known data are:

- ρ: represents the penalty associated with the overtim of a vehicle in a client.
- ω: represents the percentage of deviation allowed in the time windows. It is used to define ot_i for each client i.
- the value $M = \max(l_i + ot_i + t_{ij} + s_i - e_j), (i, j \in V)$ represents the maximum possible time consumed between two clients.

The VRP with flexible time windows and heterogeneous fleet is formulated as follows:

$$\min \sum_{c \in C} f_c \sum_{k \in S_c} \sum_{j \in N} x_{0j}^k + \sum_{c \in C} \alpha_c \sum_{k \in S_c} \sum_{\substack{i,j \in V, \\ i \neq j}} t_{ij} x_{ij}^k + \sum_{k \in K, i \in N} o_{ik} * \rho \tag{1}$$

subject to:

$$\sum_{k \in K} \sum_{\substack{j \in V, \\ i \neq j}} x_{ij}^k = 1 \ \forall \ i \in N \tag{2}$$

$$\sum_{j \in N} x_{0j}^k \leq 1 \ \forall \ k \in K \tag{3}$$

$$\sum_{i \in N} x_{i0}^k \leq 1 \ \forall \ k \in K \tag{4}$$

$$\sum_{i \in V} x_{ij}^k = \sum_{i \in V} x_{ji}^k \ \forall \ j \in V, \ k \in K \tag{5}$$

$$\sum_{i \in N} d_i \sum_{\substack{j \in V, \\ i \neq j}} x_{ij}^k \leq q_c \ \forall \ k \in S_c, \ c \in C \tag{6}$$

$$a_{ik} + s_i + t_{ij} - M(1 - x_{ij}^k) \leq a_{jk} \ \forall \ k \in K, \ i \in N, \ j \in V, \ i \neq j \tag{7}$$

$$t_{0i} * x_{0i}^k \leq a_{ik} \ \forall \ k \in K, \ i \in N \tag{8}$$

$$a_{ik} \leq (l_i + ot_i) \sum_{\substack{j \in V, \\ i \neq j}} x_{ij}^k \ \forall \ k \in K, \ i \in N \tag{9}$$

$$e_i \sum_{\substack{j \in V, \\ i \neq j}} x_{ij}^k \leq a_{ik} \leq (l_i + ot_i) \sum_{\substack{j \in V, \\ i \neq j}} x_{ij}^k \ \forall \ k \in K, \ i \in N \tag{10}$$

$$E \leq a_{0k} \leq L + ot_0 \ \forall \ k \in K \tag{11}$$

$$\sum_{k \in S_c} \sum_{j \in N} x_{0j}^k \leq n_c \ \forall \ c \in C \tag{12}$$

$$o_{ik} \geq \max(0, a_{ik} - l_i) \geq 0 \ \forall \ k \in K, \ i \in V \tag{13}$$

$$a_{ik} \geq 0 \ \forall \ k \in K, \ i \in N \tag{14}$$

$$x_{ij}^k \in \{0, 1\} \ \forall \ k \in K, \ (i, j) \in A \tag{15}$$

Eq. 1 is the objective function of the problem, that is to minimize the total cost of the proposed routing. Being S_c the set of c type vehicles, the fixed cost and the variable cost of the vehicles that make up the routes are taken into account, as well as the penalties in case of overtime.

The constraint in eq. 2 guarantees that all clients are visited by only one vehicle. Then, eq. 3, eq. 4, and eq. 5 are routing constraints, they make that if a vehicle is used it leaves and returns to the depot only by one route (the vehicle must not return from the same edge and the route must be continuous). Eq. 6 is a capacity constraint and establishes that for each route, the accumulated demand for any client must not exceed the capacity of the vehicle.

The constraint in eq. 7 establishes the precedence relationship between the arrival times of the vehicles to the clients on the routes. This constraint is the linearization of $x_{ij}^k(a_{ik} + s_i + t_{ij} - a_{jk}) = 0 \; \forall \; k \in K, \; i \in N, \; j \in V, \; i \neq j$.

The constraint 8 establishes the shortest arrival time at the first node of the path. The constraints in eq. 9, eq. 10, and eq. 11 refer to the time windows for clients and the deposit, while the constraint 12 limits the number of vehicles available for each type. Finally, the constraints in eq. 13, eq. 14, and eq. 15 restrict the values that the decision variables can take.

From the formulation of the studied problem, it is possible to demonstrate that it is a relaxation of the one proposed by Jiang et al. [5]. On the one hand, the set of feasible solutions of the proposed problem is formed by the union of two sets. The first includes solutions in which vehicles serve clients only within their original time window. The second is made up of solutions where at least one client is served outside of their original time window but within the extended one. The first set corresponds to the feasible region of the problem posed by proposed by Jiang et al. Therefore, the property stating that the feasible domain of the original problem is a subset of the feasible domain of the relaxed problem is satisfied. On the other hand, the total cost of the original problem is made up of the sum of the fixed and variable costs of the solution. While the total cost of the problem raised is made up of the fixed and variable costs and also the penalties in case of overtime. The solutions belonging to the feasible region of the original problem do not present overtime, since it is not feasible to serve a client outside their original time window. This means that in the problem presented, these solutions do not present a penalty. This is why the total costs for this set of solutions coincide in both problems. Therefore, the property that establishes that the objective function of the original problem is greater than or equal to the objective function of the relaxed problem is also satisfied.

As explained above, the two properties of the relaxation definition according to Geoffrion [3] are met. It is clear then that the problem addressed is relaxation of the problem posed by Jiang et al. [5].

2.3 Related work

The classic VRP problem was introduced by Dantzig and Ramser [2] as a generalization of the TSP applied to the distribution of gasoline, looking for the optimal route of a fleet of trucks that deliver between a terminal and several

service stations supplied by that terminal. A formulation of the integer linear programming model for the traditional VRP was proposed by Golden et al. [4].

In general, VRP can be defined as the problem of determining a series of delivery routes for a fleet of vehicles, based on one or more depots, for a certain number of geographically dispersed cities or clients. The objective is then, to satisfy the known demand of the group of clients, setting up routes of vehicles of minimum cost that originate and end in a depot. Therefore, it can be seen that TSP is a particular case of VRP, when there is only one vehicle available without restrictions on capacity or total distance traveled. Given that TSP in an NP-Hard problem and VRP is a generalization of it, VRP is also a problem of the NP-Hard class [7]. In the following years, different variants and extensions have been defined, studied and combined such as heterogeneous fleet, time windows, multiple depots, stochastic demand, pickups and deliveries, multiple trips, open routes, overloads, site dependencies, multi-vehicle task assignment , green routing, single and double container loads, two-dimensional loading, time dependencies, multiple compartments, multiple stacks and collection depots.

Solomon [10] studied the performance of heuristic methods to solve the VRP with time windows, including an early method that consists of placing all clients in a single route and then dividing the route into several smaller routes to respect the time windows, and heuristics based on Waiting-Time Limit, Nearest-Neighbor, Insertion, and Sweep. Time-Oriented Insertion Heuristic was the best method, based on selecting a seed client and from there the rest of the clients are added to the route until the vehicle capacity is completed or the allowed time period is exhausted. Seed clients are the most distant from the central depot or those with the earliest time for delivering.

Regarding exact resolution of VRP and related problems, Bladacci et al. [1] presented an exact resolution framework deriving exact algorithms that allows solving different variants of the VRP (including trained VRP, VRP with time windows, the pick-up and delivery problem with time windows, etc.), provided they can be modeled as Partition Problems with additional constraints.

In turn, many articles have proposed applying heuristics and metaheuristics [8] to solve different variants of the VRP. For the reported research, it is relevant to mention the article by Jiang et al. [5], which introduced an exact formulation for the problem (used as a reference for the problem model formulated in our research by considering flexible time windows). Furthermore, Jiang et al. proposed a two-stage resolution method by extending an existing Tabu Search procedure for VRPTW with a limited number of vehicles. and a post-processing to improve the computed solution. The efficacy of the approach was evaluated for different instances of the VRP, computing accurate results. However, the search process and effectiveness must be intensified by escalating to a larger problem.

3 The proposed exact resolution approach

This section describes the main features of the proposed resolution approach for the VRP with heterogeneous fleet and flexible time windows.

The exact resolution of the proposed model was developed in Optimization Programming Language (OPL) [11]. OPL is an algebraic modeling language for mathematical optimization model, conceived to make the development of optimization algorithms simpler than using general-purpose programming languages. OPL includes features to deal with all the main concepts in real-life optimization. OPL is part of the CPLEX software package

IBM ILOG CPLEX was used as the optimization tool, over the environment defined by Optimization Studio 12.8. Optimal solutions are computed applying a branch-and-cut heuristic, considering three stop conditions for the execution:

- The time limit for the execution (parameter `CPX_PARAM_TILIM`) was set according to the problem instance dimension:
  - Test cases with 25 clients: Limit of one hour of execution time, to compute quick solutions.
  - Test cases with 50 clients: Limit of ten hours of execution times, considered a reasonable time to obtain a solution (e.g. it allows planning routes for delivering the next day).
- Branch-and-cut tree size (parameter `CPX_PARAM_TRELIM`): 51 GB limit, restricted by the computational platform used for the experiments.
- Default GAP tolerance in CPLEX (parameter `CPX_PARAM_EPGAP`): 0.01% (0.0001). It is considered the default value since, the main goal is to compare with previous solutions obtained with that specific limit. The GAP represents, in percentage terms, the distance between the solution found and the best achievable solution. It is defined as $(f(x) - bestBound)/f(x)$, where x is the solution found and $bestBound$ is the best value achievable by the objective function.

4 Experimental results and discussion

This section describes the experimental evaluation of the proposed resolution approach.

4.1 Execution platform

The experimental evaluation was performed using computing resources from two environments with the following characteristics:

- The proposed exact method was executed on an Intel Core i5 2.7 GHz server, with 3 MB shared L3 cache, 8 GB 1867 MHz DDR3, 256 GB Flash Storage.
- Reference solutions for the non-flexible problem variant were computed in a HP ProLiant DL380 G9 server with two Intel Xeon Gold 6138 processors (20 cores each) and 128 GB RAM, from National Supercomputing Center, Uruguay (Cluster-UY) [9].

4.2 Problem instances

Two sets of instances were used, with homogeneous and heterogeneous vehicles. For homogeneous problem instances, the VRPTW test cases proposed by Solomon [10] are used. These instances include data of the locations, demands, time windows, and client service times. Six classes of instances are included: C1 and C2 have grouped clients, R1 and R2 have clients with uniformly distributed locations on a square, and RC1 and RC2 have both grouped and location clients distributed. C1, R1 and RC1 have narrow time windows and small vehicle capacity while C2, R2 and RC2 have large time windows and large vehicle capacity. In turn, for the heterogeneous problem variant, the test cases generated by Jiang et al. [5] are used. Larger vehicles have higher fixed and variable costs. Client locations, demands, time windows, and service times are derived from the benchmark test cases. This way, six new classes are generated: HC1, HC2, HR1, HR2, HRC1 and HRC2 (the H in the beginning of the instance name stands for heterogeneous). Table 1 reports the data of the employed homogeneous and heterogeneous problem instances, including the number of vehicles, their type, capacities, and both fixed and variable costs.

class	*vehicle type*	*# vehicles*	*capacity*	*fixed cost*	*variable cost*
homogeneous instances					
C1	A	25	200	80	1.0
C2	A	25	700	80	1.0
R1	A	25	200	80	1.0
R2	A	25	1000	80	1.0
RC1	A	25	200	80	1.0
RC2	A	25	1000	80	1.0
heterogeneous instances					
HC1	A	20	100	30	1.0
	B	5	200	80	1.2
HC2	A	20	400	100	1.0
	B	5	500	140	1.2
HR1	A	10	50	80	1.0
	B	15	80	140	1.2
	C	10	120	250	1.4
HR2	A	10	300	45	1.0
	B	5	400	70	1.2
HRC1	A	10	40	60	1.0
	B	20	80	150	1.2
	C	10	150	300	1.4
HRC2	A	10	100	150	1.0
	B	5	200	350	1.2

Table 1: Data of vehicles for the considered problem instances classes

Problem instances for both homogeneous and heterogeneous variants of the problem with 25 and 50 clients are considered. For all instances, ω, the allowed variation of the time windows, is defined as a percentage of its duration. Therefore, the overtime allowed in client i is calculated as $ot_i = (l_i - e_i) \times \omega$. In all the test cases considered, the value $\omega = 0.3$ was set, that is, the allowed variation of the time window is 30%.

4.3 Numerical results

Tables 2 and 3 reports the obtained results for homogeneous problem instances with 25 and 50 clients, respectively. The highlighted light gray cells indicate an optimal solution found by the proposed approach. In turn, the highlighted dark gray cells and bold font indicate a lower cost then the reference value for the non-flexible VRP obtained by Solomon [10].

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
C101	3	191.75	191.75	240	0	431.75
C102	3	190.67	190.67	240	0	430.67
C103	3	243.65	243.65	240	0	483.65
C201	2	215.48	215.48	160	0	375.48
C202	1	223.24	223.24	80	0	**303.24**
C203	2	215.48	215.48	160	0	375.48
R101	8	618.25	618.25	640	0	1 258.25
R102	3	361.18	361.18	240	0	**601.18**
R103	5	502.29	502.29	400	0	902.29
R201	2	513.49	513.49	160	3	**676.49**
R202	2	446.69	446.69	160	4	**610.69**
R203	2	503.82	503.82	160	4	667.82
RC101	3	365.17	365.17	240	21	**626.17**
RC102	3	240.00	240.00	240	2	585.34
RC103	3	415.89	415.89	240	13	668.89
RC201	3	361.18	361.18	240	0	601.18
RC202	2	376.11	376.11	160	0	**536.11**
RC203	2	369.94	369.94	160	0	**529.94**

Table 2: Results for homogeneous problem instances with 25 clients. Light gray cells indicate an optimal solution found. Dark gray cells and bold font indicate a lower cost then the reference value for the non-flexible VRP by Solomon [10]

Results in Table 2 indicate that the proposed approach computed competitive results for homogeneous problem instances with 25 clients, including six optimal solutions and other seven solutions with lower cost then the reference value for the non-flexible VRP.

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
C101	5	363.13	363.13	400	0	763.13
C102	5	362.05	362.05	400	0	762.05
C103	No Solution Found					
C201	3	361.68	361.68	240	0	**601.68**
C202	3	391.59	391.59	240	0	**631.59**
C203	3	410.06	410.06	240	0	**650.06**
R101	11	1020.96	1020.96	880	8	1908.96
R102	6	714	714	480	24	1218
R103	11	1110.75	1110.75	880	0	1990.75
R201	4	873.15	873.15	320	6	1199.15
R202	5	775.81	775.81	400	0	1175.81
R203	5	697.06	697.06	400	0	1097.06
RC101	8	897.98	897.98	640	29	**1566.98**
RC102	No Solution Found					
RC103	8	814.07	814.07	640	0	**1454.07**
RC201	5	704.75	704.75	400	24	1128.75
RC202	5	858.36	858.36	400	0	1258.36
RC203	6	989.22	989.22	480	0	1469.22

Table 3: Results for homogeneous problem instances with 50 clients.

Regarding homogeneous problem instances with 50 clients, two optimal solutions were found, and other five solutions with lower cost then the reference value for the non-flexible VRP. The proposed model was not able to compute an exact solution in the specified time limit for two instances with 25 vehicles (C103 and RC102).

Tables 4 and 5 reports the obtained results for heterogenous problem instances with 25 and 50 clients, respectively. In this case, since there are three types of vehicles to use in the fleet (A, B, or C), column *# vehicles* indicates the type and the number of vehicles used.

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
HC101	3A - 1B	230.07	249.24	170	0	419.24
HC102	5A	305.87	305.87	15	0	455.87
HC103	5A	340.56	340.56	15	0	490.56
HC104	5A	292.05	292.05	15	0	**442.05**
HC105	3A - 1B	230.07	249.24	170	0	419.24
HC106	3A - 1B	230.07	249.24	170	0	419.24
HC107	3A - 1B	223.85	244.04	170	0	414.04
HC108	5A	292.51	292.51	15	0	442.51

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Table 4 – *Continued from previous page*

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
HC109	5A	303.63	303.63	15	0	453.63
HC201	2A	215.48	215.48	20	0	415.48
HC202	2A	294.24	294.24	20	0	494.24
HC203	2A	248.95	248.95	20	0	448.95
HC204	2A	258.61	258.61	20	0	458.61
HC205	2A	215.48	215.48	20	0	415.48
HC206	2A	215.48	215.48	20	0	415.48
HC207	2A	217.31	217.31	20	0	417.31
HC208	2A	246.59	246.59	20	0	446.59
HR101	8A	647.86	647.86	64	0	1287.86
HR102	4A - 4B	731.61	828.09	990	0	1818.09
HR103	6A - 1B	650.55	668.73	620	8	1296.73
HR104	7A	582.52	582.52	56	3	1145.52
HR105	6A - 1B	655.81	679.06	620	14	1313.06
HR106	6A - 1B	628.27	653.12	620	0	1273.12
HR107	6A - 1B	640.67	664.96	620	0	1284.96
HR108	7A	589.18	589.18	56	0	1149.18
HR109	8A	725.14	725.14	64	0	1365.14
HR110	6A - 1B	634.08	654.99	620	3	1277.99
HR111	8A	664.78	664.78	64	0	1304.78
HR112	7A	655.31	655.31	56	10	1225.31
HR201	2A	500.27	500.27	90	7	**597.27**
HR202	3A	424.31	424.31	135	4	563.31
HR203	2A	417.83	417.83	90	4	511.83
HR204	2A	406.12	406.12	90	5	501.12
HR205	2A	405.89	405.89	90	7	502.89
HR206	2A	442.99	442.99	90	0	532.99
HR207	2A	409.89	409.89	90	0	499.89
HR208	2A	354.96	354.96	90	0	444.96
HR209	2A	472.17	472.17	90	0	562.17
HR210	2A	413.24	413.24	90	0	503.24
HR211	2A	358.88	358.88	90	0	451.88
HRC101	4A - 5B	774.08	860.87	990	0	1850.87
HRC102	4A - 3B - 1C	715.76	813.35	990	1	1804.35
HRC103	4A - 3B - 1C	786.10	900.75	990	0	1890.75
HRC104	4A - 5B	803.68	897.53	990	1	1888.53
HRC105	2A - 6B	774.75	895.45	1020	69	1984.45
HRC106	4A - 5B	799.63	891.19	990	0	1881.19
HRC107	2A - 6B	804.69	920.68	1020	2	1942.68
HRC108	4A - 3B - 1C	738.60	845.20	990	0	1835.20

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Table 4 – *Continued from previous page*

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
HRC201	4A - 1B	499.60	524.54	950	0	1474.54
HRC202	6A	554.32	554.32	900	0	1454.32
HRC203	6A	531.89	531.89	900	0	1431.89
HRC204	6A	597.25	597.25	900	0	1497.25
HRC205	6A	563.45	563.45	900	0	1463.45
HRC206	4A - 1B	446.99	467.84	950	0	1417.84
HRC207	2A - 2B	373.98	414.57	1000	0	1414.57
HRC208	6A	512.56	512.56	900	0	1412.56

Table 4: Results for heterogeneous problem instances with 25 clients.

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
HC101	7A - 1B	519.47	538.91	290	0	828.91
HC102	8A - 1B	532.10	551.27	320	0	871.27
HC103	10A	694.16	694.16	300	0	994.16
HC104	7A - 1B	590.55	611.25	290	0	**901.25**
HC105	7A - 1B	522.81	542.25	290	0	832.25
HC106	5A - 2B	457.14	495.75	310	0	805.75
HC107	7A - 1B	563.54	582.71	290	0	872.71
HC108	9A	633.65	633.65	270	0	**903.65**
HC109	8A - 1B	691.31	716.79	320	0	**1036.79**
HC201	3A	391.32	391.32	300	0	691.32
HC202	3A	405.58	405.58	240	0	**645.58**
HC203	4A	428.57	428.57	400	0	**828.57**
HC204	3A	424.75	424.75	300	0	724.75
HC205	3A	390.93	390.93	300	0	**690.93**
HC206	4A	425.22	425.22	400	0	825.22
HC207	2A - 1B	479.62	503.96	340	0	843.90
HC208	3A	472.99	472.99	300	0	772.99
HR101	9A - 4B	1120.72	1188.67	1280	7	2475.67
HR102	9A - 3B - 1C	1191.54	1286.24	1390	2	**2678.24**
HR103	9A - 4B	1315.78	1390.69	1280	4	2674.69
HR104	9A - 4B	1104.15	1183.58	1280	0	**2463.58**
HR105	7A - 4B - 1C	1121.40	1241.69	1370	18	2629.69
HR106	7A - 6B	1245.71	1369.79	1400	12	2781.79
HR107	9A - 4B	1185.85	1276.34	1280	22	2578.34
HR108	7A - 4B - 1C	1012.40	1133.14	1370	0	2503.14
HR109	8A - 5B	1062.83	1143.81	1340	1	2484.81
HR110	9A - 4B	1292.15	1375.08	1280	3	2658.08
HR111	8A - 5B	1067.85	1149.89	1340	7	2496.89
HR112	9A - 4B	1057.01	1126.20	1280	0	2406.20

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Table 5 – *Continued from previous page*

instance	*# vehicles*	*distance*	*variable cost*	*fixed cost*	*penalty*	*total cost*
HR201	4A	786.30	786.30	180	28	**994.30**
HR202	5A	753.26	753.26	225	0	978.26
HR203	5A	758.88	758.88	225	0	983.88
HR204	3A	725.26	725.26	135	0	860.26
HR205	5A	801.85	801.85	225	0	1026.85
HR206	5A	818.31	818.31	225	0	1043.31
HR207	4A	730.46	730.46	180	0	910.46
HR208	4A	628.95	628.95	180	0	808.95
HR209	3A	737.55	737.55	135	4	876.55
HR210	4A	851.74	851.74	180	0	1031.74
HR211	3A - 1B	756.39	786.07	205	0	991.07
HRC101	5A - 10B	1336.05	1523.73	1800	1	3324.73
HRC102	10A - 6B - 1C	1567.88	1715.43	1800	0	3515.43
HRC103	7A - 9B	1467.14	1628.40	1770	4	3402.40
HRC104	5A - 8B - 1C	1528.34	1774.68	1800	8	3582.68
HRC105	9A - 8B	1601.23	1756.72	1740	0	3496.72
HRC106	4A - 9B - 1C	1301.14	1509.47	1890	3	3402.47
HRC107	5A - 8B - 1C	1375.61	1574.59	1800	0	3374.59
HRC108	5A - 8B - 1C	1485.06	1681.17	1800	0	3481.17
HRC201	9A - 1B	1247.40	1279.34	1700	0	2979.34
HRC202	8A - 1B	1269.05	1312.81	1550	0	2862.81
HRC203	7A - 2B	1159.84	1229.34	1750	0	2979.34
HRC204	8A - 1B	1130.16	1150.66	1550	0	2700.66
HRC205	9A - 1B	1150.88	1197.16	1700	0	2897.16
HRC206	9A - 1B	1278.85	1310.59	1700	0	3010.59
HRC207	10A	1288.54	1288.54	1500	0	2788.54
HRC208	8A - 1B	1138.90	1175.38	1550	0	2725.38

Table 5: Results for heterogeneous problem instances with 50 clients.

Results in Tables 4 and 5 indicate that the problem using heterogeneous vehicles is significantly harder to solve to optimality for the proposed approach. Only six optimal solutions were found within the considered execution time limit, five for instances with 25 clients and one for instances with 50 clients. For the other instances, it is not guaranteed that the solution computed using CPLEX is the optimal (i.e., the branch and bound method stop after reaching the execution time limit with a GAP value large than the default GAP tolerance (parameter `CPXPARAMEPGAP`). However, the proposed model was able to find solutions for all problem instances solved, unlike in the case for 25 vehicles.

On the other hand, the proposed model using flexible time windows was able to compute eleven solutions with lower cost than the optimal value for the fixed time windows problem variant, for heterogeneous instances.

5 Conclusions and future work

This article presented an exact resolution approach for the VRP with heterogeneous fleet and flexible time windows. The studied problem variant extends the classical VRP formulation by considering flexible (i.e., extended) time windows for delivering products to clients, accounting for a more realistic setting in nowadays scenarios. A penalization is included in the cost function for those vehicles arriving after the end of the time window of a client.

The proposed approach is based on a linear programming formulation implemented using the OPL languaje, in CPLEX. The experimental evaluation focused on evaluating the quality of solutions for two sets of problem instances modeling homogeneous and heterogeneous fleets, built by extending benchmark test cases from the related literature.

Accurate results were reported for the proposed linear programming model. It was able to solve 146 out of the considered 148 problem instances in reasonable execution times. A total number of 16 problem instances were solved to optimality and other 23 solutions accounting for routes with lower cost than for the non-flexible problem variant.

The main lines for future work are related to extend the validation of the proposed approach, and using heuristic/metaheuristic algorithms to efficiently address larger problem instances. The problem model can be extended to a multiobjective formulation by considering trade-off solutions for the simultaneous optimization of the total cost and the quality of service offered to clients.

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Determinants of Smart city commitment among citizens from Bahía Blanca, Argentina

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Abstract. This paper aims to examine the determinants of smart cities activities across individuals from Bahía Blanca, Argentina. Literature has identified different factors explaining citizens' commitment with smart cities, such as education, age, labor condition; and other more subjective factors such as trust and awareness about the smart city concept. A critical determinant of smart commitment is e-readiness or digital readiness; that is, the level of preparedness to properly exploit internet opportunities such as e-government and e-commerce. To achieve this goal, we used a survey conducted on 97 citizens following Moderniza Bahía Facebook from Bahia Blanca, Argentina. By estimating a structural equation model, we obtained that higher levels of ICT use are associated with higher levels of smart city commitment, and that higher awareness of the smart city concept relates to higher levels of smart city commitment. Demographic factors such as age and labor condition also explain ICT use. These insights are useful for city stakeholders and policy makers to design properly smart city policies and strategies for citizen engagement.

Keywords: smart cities; ICT use; demographic factors.

1 Introduction

"Smart cities [which] are a new style of city providing sustainable growth and designed to encourage healthy economic activities that reduce the burden on the environment while improving QoL (Quality of Life) (JSCP, 2012)". We are witnessing a more interconnected and challenging framework that imposes the need to find better solutions for information sharing and transfer among multiple actors involved in shared environments, such as urban cities (Di Nauta et al. 2015).

Under this smart city's scenario, information and communication technology infrastructures are critical tools to improve and support social and urban growth, promoting citizens' participation and governmental efficiency. The adoption of ICT is critical for the performance of smart cities and for the performance of smart activities from the citizen perspective. Smart city services offer citizens a better living envi-

ronment and raise their quality of life (Lee et al., 2014; Piro et al. 2014; Yigitcanlar and Lee, 2014). There are many examples of smart city services such as end-to-end applications that focus on common concerns such as mobility, public services, and safety.

Since urban services are used by citizens, it is of main importance to take account their opinions and perceptions for a correct management of the services (Yeh, 2017). Nowadays, cities do not have a deep enough understanding of their citizens to actively and effectively engage them (European Commission 2013, p. 12). Scholars have highlighted that little research has focused on examining the citizens' commitment with smart cities such as smart practices or activities (Granier and Kudo, 2016). The authors concern there is a gap between the recent political approach that focus on citizens' "engagement" or "participation" in smart cities and the lack of research related to this issue. In fact, the smart city differs from the digital city in the focus given to the relationships among the actors and entities involved and their contribution to the success of all (Nam and Pardo, 2011). However, some recent empirical literature has stressed evidence on the factors that motivate citizens engagement in smart cities (Polese et al., 2018; Cardullo and Kitchin, 2017; Yeh, 2017).

The framework of this study is in line with the Innovation Diffusion Theory and incorporates the allegations in the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh et al. 2003). Based on UTAUT, citizens (users) with different demographic characteristics would act differently regarding the usage of technology. Building on this reflection, this study provides some understanding on factors that relate to the success or failure of citizens' engagement on smart cities initiatives through an explorative study on the smart city landscape. To achieve these goals, we utilize an online survey conducted to a group of citizens from Bahía Blanca.

In Argentina, 69.4% of individuals use the Internet (two out of three people use the Internet), but only 16.1% of inhabitants have a fixed broadband subscription. On the other side, the active mobile broadband subscription is higher than the fixed broadband reaching 67% (ITU, 2016). Bahía Blanca is a city of about 400 thousand inhabitants located in the southwest of Buenos Aires Province, Argentina. Bahía Blanca is also one of the Argentinean cities beneficiated by the program Pais Digital. Based on the latest data on ICT diffusion at household level published by INDEC in the 2017 technical report, Bahía Blanca is one of the fifth urban places in Argentina with the highest percentage of household using Internet. A better exploitation of the Internet opportunities depends on the education level of population and their digital skills. In this aspect, data based on EPH (Household Permanent Survey) 2016, shows 34% of people older than 25 holds a tertiary or university level complete in the conglomerate Bahia Blanca Cerri. Moreover, 60% of people older than 20 have at least the secondary school complete.

The paper is structured as follows. First, we describe the theoretical framework related to smart cities necessary to establish the hypotheses of the study. Secondly, the methodology and data are explained. Thirdly, we show the results obtained by estimating the structural model and finally, results and conclusions are provided Please note that the first paragraph of a section or subsection is not indented. The first paragraphs that follows a table, figure, equation etc. does not have an indent, either.

2 Theoretical Framework

During the last years, some research has emerged towards the importance of building Smart Cities. Although the concept is not new and there is plenty of definitions, we can distinguish two different approaches. On the one side, a technological view that centers on the ICT role as a mean to deepen and strengthen access to public information and turn city services more efficient (Belissent and Girón, 2013; Nam and Pardo, 2011; Washburn et al., 2010; Paskaleva, 2009; Caragliu, Del Blo and Nijkamp, 2011). On the other side, a wider approach that is related to notions of sustainable economic growth, quality of life, participatory governance, and the reduction of emissions that places the citizen at the center of analysis (Albino et al., 2015; Anthopoulos and Fitsilis, 2010; Winters, 2011; Topetta, 2010; Caragliu et al., 2011; Shapiro, 2006). "The spirit of e-governance in a smart city should be citizen-centric and citizen-driven" (Albino et al. 2015, p. 12). Most definitions of smart cities in this side coincide in five features or characteristics: smart economy, smart governance, smart mobility, smart environment and smart people.

At the same time, evaluation of citizens' perceptions in respect to urban innovations has become relevant (Macke, 2018, Marsal Llacuna, 2015). Macke (2018) focuses on the wider definition of smart cities and evaluates the perception of quality of life of Curitiba, Brazil. From a theoretical perspective, the Diffusion of Innovation theory (DOI) (Rogers, 1962) offers a model to explain the social and technological factors that affect the acceptance of innovative Information Technology (IT). This theory is broadly employed for comparison of initial adoption and continued use in a variety of technologies (Agarwal and Prasad, 1997). Later on, Moore and Benbasat (1991) have proposed the Innovation Diffusion Theory (IDT), which is an extension of DOI theory but it also includes in the ICT adoption a moderating factor termed "personal innovativeness". This term represents an individual's propensity to innovate (Agarwal and Prasad, 1998). If users are more novelty seeking, they may be more accepting innovative technologies. IDT focuses on the technological aspects and then incorporates the users' behaviour and social factors associated with an innovative technology.

Recent empirical evidence has analysed the determinants of citizens' engagement in smart cities initiatives. For instance, Cardullo and Kitchin (2017) analyse the role and context of citizens in smart cities by examining smart city initiatives in Dublin, Ireland which they titled as ''the scaffold of smart citizen participation''. Besides, Polese et al. (2018) offers an empirical investigation from a sociological and psychological perspective, on the perception of citizen services in the city of Brno, Czech Republic. The study centres on the "smart cities" issue as an example of complex service systems (CSSs) and shows how actors' perceptions (cognitive and psychological dimensions) can influence opportunities and willingness for value co-creation and collaboration. Similarly, Caputo et al. (2016c, 2017b) and Saviano et al. (2016) analyse the role of individual perceptions in the evaluation of services and in the definition of possible collaborative behaviours, with specific reference to the domain of the "smart city". On the other side, Yeh (2017) examine citizens from Taiwanese cities

that have participated in smart cities campaigns. Citizens will use smart cities services if they are innovative, high quality and secure (in terms of privacy).

2.1 SC Activities or SC commitment

Many studies show citizens from smart cities have a strong commitment with the development of sustainable and scalable practices such as trash recycling, efficient use of energy resources, among others (Chourabi et al., 2012; Khansari et al., 2014; de Jong et al., 2015; Belanche et al., 2016). Moreover, processes of political and electronic participation are a baseline in development of Smart Cities (Afzalan et al. 2017; Neirotti et al. 2014).

From an environmental perspective, Sovacool (2014) expresses citizens' participation increase democracy. Citizens perceive they are represented in environmental decision-making. Besides, public engagement and learning lead to a behavior change of environmental issues (Bull et al, 2008). Bull and Azennoud (2016) offer an example of citizen engagement in Hampshire, USA. A discussion of an adequate waste strategy was performed to engage the public in decision management of household waste in the city.

2.2 ICT use and SC Activities

By using ICT, public services can be offered online, public information can be easily accessed and citizens can organized among them to share interests and concerns. Moreover, ICT use can facilitate and promote citizens' decision-making and involvement in public life (Vázquez and Vicente, 2019). ICT plays a key role in Smart Cities to connect infrastructures, government and citizens (European Commission, 2013). Paskaleva (2009) highlights that the smart city is based on the "use" of advantages offered by information and communication technology.

Socio-economic demographics differences can give rise to a digital infrastructure gap between cities in emerging economies, such as India, asking for smart city policies implementation (Praharaj et al., 2017). However, in some countries such as India, most technologically advanced cities like Ahmedabad had only 10.3% of its household accessing internet as of the year 2011 (Praharaj et al., 2017). Therefore, ICT access has not been considered a basic infrastructure for building Smart Cities in less developed countries.

ICT have an increasing effect on different facets of people's overall quality of life (Yeh, 2017; Khankhoje, 2004; Deakin, 2014; Makee et al., 2014; Veeckman and van der Graaf, 2015). The technology trends such as mobile, personal devices; broadband connectivity; open data; urban interfaces; and, cloud computing are progressing at a rapid pace. The adoption of ICT applications in e-government is a prerequisite for the emergence of smart cities. By doing e-government, citizens can communicate with governments from different levels (national, federal, regional, local). As a result, citi-

zens' involvement in public sectors governance leads to the improvement of efficiency and effectiveness

ICT use will depend not only on connectivity (Internet access) and on access to digital devices such as computers, tablets, mobile phones, among others, but also on ICT skills. This relationship between access and use is due to the existence of complementarities in the ICT diffusion (Dewan et al., 2010). Personal computers have a stronger impact on the Internet diffusion in developing than in developed countries. Usually, the unequal access to resources and rights is correlated with both ICT appropriation and ICT intensity use. Then, we can state the first hypothesis:

Hypothesis 1: ICT use positively affects citizens' performance of SC activities.

2.3 Awareness of the SC concept and SC activities

Studies based on IDT have shown that the perceived characteristics of innovation can have a significant effect on adopters' behaviours toward the acceptance and usage of innovative ICT solutions (Plouffe et al., 2001), egovernment systems (Carter and Bélanger, 2005; Gilbert et al., 2004; Shareef et al., 2007) and SC services (Yeh, 2017). Similarly, awareness of the smart city concept is a main factor to explain a smart citizens' behaviour. However, Neirotti et al. (2014) find a negative relationship between awareness and SC activities. A possible explanation is that the most polluted cities are located in developing countries in which complete awareness of the SC concept has not yet been established.

Hypothesis 2. The awareness of the SC concept positively affects citizens' performance of SC activities.

2.4 Trust and SC activities

Trust is generally understood as the willingness of one person to count on the behaviours of others, especially when this person is under a vulnerable situation. Trust always supposes the person is ready to accept a certain degree of risk and to become vulnerable to a trusted party (Hosmer, 1995). This approval of risk is based on the expectation that the trusted party will perform actions that are important or beneficial to the vulnerable party (Eid, 2011).

If Citizens trust in the ICT-based SC services, they will positively accept and use the ICT-based SC services (Yeh, 2017). However, Vazquez and Vicente (2019) do not find trust on governments is a significant factor to explain e-participation, which is one of the dimensions of smart cities (smart governance). Therefore, we can pose hypothesis 3.

Hypothesis 3: Citizens' trust in e-goverment positively affects citizens' performance of SC activities.

2.5 Demographic factors and SC activities

Demographic characteristics affect the use of a given product or service (Webb et al., 2012), probably because the needs of citizens vary according to their educational level, gender and age. However, results on the impact of demographic factors on usage are not conclusive. Yeh (2017) show Taiwanese citizens' attitudes and behaviours toward ICT based SC services are not affected by their demographic characteristics in terms of age, gender, and education reinforcing the public nature of services, which are oriented toward the whole community. On the other side, Vázquez and Vicente (2019) observe socioeconomic factors such as age, educational attainment and labour situation are significant factors to explain citizens' e-Participation, while gender is not significant.

Citizens' education is one of the main determinants of people's digitalization level (Gutiérrez et al.,2010). The educational condition is a significant predictor of ICT use. An educated individual can access cognitive resources, digital skills and more important, social and knowledge resources. Some studies have claimed that education affects the probability of using Internet (Vicente and López, 2006) and the diffusion of Internet (Kiiski and Pohjola, 2002; Hargittai, 1999). In particular, Hargittai (1999) observes that education significantly enhanced the penetration level of Internet hosts across countries. Besides, Kiiski and Pohjola (2002) show that mean years of schooling is a significant factor to explain the growth of Internet hosts per capita. On the other side, Chinn and Fairlie (2007) did not observe a significant correlation between the variables.

Hence, education can indirectly determine the development of SC activities. In this line, Belanche, Casaló and Orús (2016) show citizens' educational level positively affects urban services usage since the more educated the people, the higher the environmental consciousness will be. The higher the educational level (human capital), the greater the probability of using ICT will be. People that are more educated have better access to information about the SC benefits and how to perform intelligent activities. Hence, the development of SC activities will be higher.

Hypothesis 4: The more educated the people, the higher the ICT use; and therefore, the higher the citizens' performance of SC activities will be.

Gender is also considered an important factor to predict the use and acceptance of technology related applications or systems. The decision-making processes are different between men and women (Tarhini, Hone, and Liu, 2014; Al-Shafi and Weerakkody, 2010; Wang et al., 2009; Dwivedi and Williams, 2008).

Hypothesis 5: Men are more likely to ICT use than women are; and therefore, they are more likely to perform more SC activities than women are.

On the other side, older people perceived lower potential profits from innovating than younger people because they attribute a higher discount rate to future profits. While young people are more prone to have ICT access (Grazzi and Vergara, 2011), older people usually use the Internet to a lesser extent (Gutiérrez et al., 2010; Barrantes, 2007). There are differential effects regarding the affect-creativity association, dependent on employees' age (Volmer et al., 2018). Therefore, age is a proxy of personal innovativeness and can be employed as a preliminary factor to understand the characteristics of adopters (Agarwal et al., 1998) and the level of Acceptance/Usage of ICT-based SC services (Yeh, 2017).

Hypothesis 6: The older people are less likely to ICT use and, therefore, to perform SC activities mediated by ICT such as e-commerce, e-government, among others.

Finally, income is an important determinant of ICT adoption as it indicates the households' budget constraint (Grazzi and Vergara, 2011; Barrantes, 2007; Vicente and Lopez, 2006). One of the users' characteristics that affect the intra-country digital divide is related to income (Zhang, 2013). The greater the household income, the higher the probability of using the Internet is (Alderete, 2018). The lack of income does not allow citizens to take part in the ICT demand. Therefore, unemployed or people with a transitory job are less likely to use ICT.

Hypothesis 7: Citizens with a permanent job are more likely to use ICT, and therefore, to perform SC activities.

Based on this research background, the model examines the causal relationship among the smart cities activities and demographic factors by describing the mediating role of ICT use. Hence, citizens' gender, age, education level and labour condition are the control variables of the proposed framework by explaining directly ICT use, and Indirectly SC activities. Figure 1 offers a graphical representation to explain the model.

3 Methodology

We use data obtained from an online survey directed to the followers of the Facebook fan page "Moderniza Bahía". The survey was conducted between April and May 2019 and was supported by the Secretary of Modernization of Bahía Blanca Town Hall. During these two months, we collected data from 97 citizens.

The questionnaire was based on several literature sources on e-government and smart cities (Weeradoky et al.2016; Alshehri et al. 2012; Chen, 2010; Teo et al., 2008). It collects information about the citizens' profile (age, education, labour condition, and ICT use), smart cities and e-government. Questions are closed and most of them are Likert scale questions.

The size of the sample is 97; we collect 97 valid observations during the two months period of diffusion of the survey. The sample size is enough for a finite popu-

lation sampling (lower or equal than 100000) (Vázquez y Trespalacios, 2002). The sample responds to the following formula:

$$n = \frac{Z^2 * N * P(1-P)}{(N-1) * K^2 + Z^2 * P(1-P)}$$

Where N is total population. In this case, followers of Moderniza Bahía Facebook., N=16400 by April 2019.

Z is the value obtained from significance levels. If population distribution is normal at a significance level of 95%, z value is 1.96. In this case, with a significance level of 90%, the corresponding z is 1.645; and so on.

K is the error or maximum difference between the sample proportion and the population proportion to be accepted based on the significance level proposed. For a significance level of 95%, k is 0.05; similarly, for a significance level of 90%, k is 0.1, as in this case.

P is the population fraction of interest. A parameter that indicates the percentage of population interested in smart cities. It can be obtained from a pilot survey; but if it is an unknown parameter, as in this case, it is suggested to use the most unfavourable value of 50%.

For each question, respondents were asked to declare their opinion using a five-point Likert scale (Matell and Jacoby, 1971) in which 1 = "strongly disagree" and 5 = "strongly agree."

We study the relationship between Smart city activities and ICT use by estimating a Structural Equation Modelling (SEM). Although there are different statistical packages, we utilize STATA 14 to perform the estimations. STATA software only uses CB-SEM (Bernardes do Nascimento and da Silva Macedo, 2016).

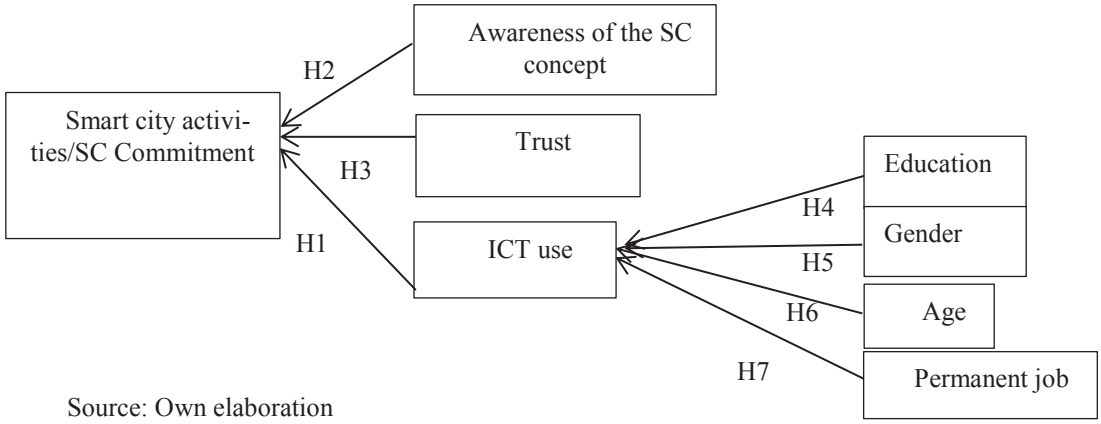
In this frame, SEM models are of two different types with regard to the statistical approach (non-parametric or parametric testing), the objective of the study (exploratory or confirmatory), and, especially, the algorithm employed (Generalized Least Square (GLE) or Maximum Likelihood Estimator (MLE))(Esposito, 2009). These differences lead to Variance Based Structural Equation Modeling (VB-SEM) and the Covariance Based Structural Equation Modeling (CB-SEM), respectively.

This paper uses a CB-SEM model, which is SEM based on the covariance matrix. CB-SEM goal is to test and confirm the theory by using data (exploratory model). The difference between the theoretical covariance matrix and the estimated covariance matrix (based on data) is minimized to estimate the parameters (Hair et al., 2011). Indicators of goodness of fit arise due to the difference between the empirical and theoretical covariance matrix (Hair et al., 2009),

On the other side, there are PLS (Partial Least Square) models which are SEM models based on the variance matrix (VB-SEM). However, PLS-SEM objective is building theory based on the emerging relationships (in the same way as multiple regression analysis). Thus, it is a more exploratory model. PLS-SEM emerges from the discrepancy between the observed values and/or the dependent latent variables and the values estimated by the model (Hair et al., 2011). Hence, measures or indicators of the predictive capacity of the model using PLS-SEM are of main importance to determine the quality or goodness of fit of the model, such as reliability, explained

variance, among others; which is not needed in CB-SEM models (Henseler et al., 2009). Figure 1 shows the causal relationships to be tested.

Figure 1.The model to be estimated



Source: Own elaboration

3.1 Variables

The structural model is compound of two structural equations since there are two endogenous variables: SC activities and ICT use.

SC activities: SC activities is a variable (non-observable) obtained by using a factorial analysis among a set of indicators (Table 1).

Table 1. Communalities from factor analysis among SC activities

Smart City dimension	SC activities	Initial	First extraction	Second extraction
Smart environment	Reduction of private transports (car. moto)	1.000	.597	.607
	Use of public transport	1.000	.698	.699
	Use of bike lanes	1.000	.391	
	Recycle or classify waste	1.000	.606	.760
	Rational water consumption	1.000	.723	.742
Smart government	Interaction with local government through internet (e-government)	1.000	.515	.497
Smart economy	Electronic commerce (sale-buy through internet)	1.000	.495	.509

Smart mobility	Use of SAMPEM Parking (parking app)	1.000	.562	.586
Smart people	Home-banking or financial transaction online (i.e.: pay taxes)	1.000	.738	.739
	E-learning	1.000	.617	.652

Source: Own elaboration.

To develop a construct or variable for measuring SC activities in citizens from Bahía Blanca, a set of items were included based on a thorough review of the smart city literature and mainly on the project's questionnaire. Citizens were asked to provide information about the kind of smart activities performed from reduction of public transport to e-learning.

Both the Kaiser-Meyer-Olkin Measure of Sampling Adequacy and the Bartlett's test of sphericity indicate that the factor analysis may be useful with the data. The KMO measure of sampling is nearly 0.6, if the value were less than 0.50, the results of the factor analysis probably will not be very useful. On the other side, the p value related to the Bartlett's test of sphericity is zero, indicating that these variables are related and therefore suitable for structure detection.

Table 1 shows communalities from each SC activity acquired by performing a Component Principal Analysis. We observe that the item or variable "Use of bike lane" is not relevant for explaining the variance (since communality from the first extraction is lower than 0.4). Then, we made the second extraction to define the significant items. After that, by using the components extracted, we build the SC activities index. Table 2 reports the first four factors that explain nearly 64 per cent of the variance.

Table 2. Total variance explained

Components	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	% accumulated	Total	% of variance	% accumulated	Total	% of variance	% acummulated
1	2.021	22.459	22.459	2.021	22.459	22.459	1.919	21.321	21.321
2	1.521	16.903	39.362	1.521	16.903	39.362	1.609	17.874	39.195
3	1.222	13.579	52.941	1.222	13.579	52.941	1.166	12.956	52.152
4	1.026	11.403	64.343	1.026	11.403	64.343	1.097	12.192	64.343
5	.847	9.417	73.760						
6	.754	8.375	82.135						
7	.662	7.358	89.493						
8	.530	5.890	95.383						
9	.415	4.617	100.000						

Extraction method: Principal Components analysis

To construct the SC activities index, we compute the weighted sum of the four components. Each weight represents the proportion of variance of each component related to total variance. The average value of the SC activities index reaches 0.51.

ICT use: This variable represents an independent explanatory factor of SC activities. The hypothesis is the higher the ICT use, the higher the propensity of developing SC activities such as e-commerce, e-government, among other.

ICT use is also an endogenous variable in the model, which is mainly explained by demographic factors. We use the same methodology as the SC activities index to build the variable ICT use. ICT use is a variable obtained from a factorial analysis among a set of ICT use indicators. People were asked to provide information about the places use to connect Internet as well as the devices employed. The higher the number of places and devices used to connect internet, the higher the intensity of using Internet will be.

Since we have built ICT use as an exogenous variable by using factor analysis, we show the suitability of the data for structure detection. Both the Kaiser-Meyer-Olkin Measure of Sampling Adequacy (nearly 0.52) and the Bartlett's test of sphericity (p value 0.000) indicates that the factor analysis may be useful with the data. Tables 3 and 4 shows information needed to this task.

Table 3. Communalities from factor analysis in ICT use

	Initial	First Extraction	Second Extraction
Internet Access at home	1.000	.862	.868
Internet Access at work	1.000	.581	.702
Internet Access in educational places	1.000	.572	.571
Internet access in commercial places	1.000	.625	.670
Internet Access in Public places	1.000	.701	.736
Use computer to connect Internet	1.000	.656	.689
Use mobile phones to connect internet	1.000	.870	.872
Use Tablet to connect Internet	1.000	.363	
Use TV to connect Internet	1.000	.449	.468
Use E-Reader to connect Internet	1.000	.487	.478

Source: Own elaboration

Table 4. Total variance explained

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of Variance	Accumulated%	Total	% of Variance	Accumulated%	Total	% of Variance	Accumulate
1	1.948	21.646	21.646	1.948	21.646	21.646	1.714	19.048	19.048
2	1.684	18.715	40.362	1.684	18.715	40.362	1.651	18.347	37.395
3	1.302	14.469	54.830	1.302	14.469	54.830	1.382	15.357	52.752
4	1.120	12.446	67.277	1.120	12.446	67.277	1.307	14.524	67.277
5	.936	10.398	77.675						
6	.751	8.339	86.014						
7	.571	6.340	92.354						
8	.434	4.824	97.178						
9	.254	2.822	100.000						

Extraction method: Principal Components analysis

Source: Own elaboration

Independent variables of SC Activities:

Web-Trust: trust in the web is an important factor of the willingness of citizens to doing e-commerce, e-government, among other SC activities. Web trust refers to trust in the municipality's website; is an ordinal Likert scale variable that ranges from 1 (totally disagree) to 5 (totally agree).

SC-Awareness: it related to how much local citizens are aware of the Smart Cities concept. The survey asks each citizen if he was acquainted with the smart cities concept. It's an ordinal variable that ranges from "have never heard about that" to "I have heard about it but I do not know much"; "I know the concept, what it means and how cities are implementing it"; "I am researching about smart cities ideas" and lastly, "I am planning or implementing one or more smart cities projects."

Independent variables of ICT use:

Age: Age is a scalar and continuous variable. Each participant is asked to report his or her age in the survey.

Education: High_education is a binary variable that takes value 1 if the individual has reached a tertiary or university degree and zero, otherwise (whose maximum education level is lower than tertiary).

Income: Permanent_job is a binary variable that values 1 if the individual works in a permanent job, and zero otherwise. The survey does not collect information on income. However, labour condition can be a proxy of income. We suppose citizens without a permanent job are in a more vulnerable condition to support connectivity and therefore, ICT use than the rest (people with transitory or informal jobs; unoccupied; among others).

Gender: A binary variable that takes value one if the individual is a man and zero if it is a woman.

4 Results

This SEM model does not include a measurement model since there are no latent variables. Due to the limited number of observations, we do not add latent variables but include non-observable variables (such as ICT use, SC activities) by using factorial analysis.

In this section, we test the goodness of fit of the structural model (Table 5). The Chi Square test is a test of exact fit that confirms the structural equation model estimated can explain the theoretical model. Chi square values near zero shows an adequate goodness of fit. Based on this model, Chi square is 6.4 with a p-value of 0.38. As a result, the hypothesis of a perfect correspondence between the estimated matrix and the observations matrix cannot be rejected.

On the other side, we analyse the Root Mean Square Error of Approximation (RMSEA) to provide a more sensible approach than the Chi Square test. The model fit is good if RMSEA is lower than 0.05 and does not surpass the lower bound of the 90 percent confidence interval (Steiger, 1990). We can determine the model fits well because RMSEA reaches a value zero.

Moreover, there is an overall measure of bad fit known as the Root Mean Square Residual index (RMR). This indicator is based on the fitted residuals that are scale dependent (]öreskog and Sörbom, 1981). Therefore, the Standard RMR (SRMR) is a more accurate indicator. If SRMR is lower than 0.05, it indicates a good fit of the model (Hu and Bentler, 1995).

Table 5. Goodness of fit of the structural model

Statistic	Value	Description
Likelihood Ratio		
Chi square_ms(6)	6.405	model vs. saturated
p > chi square	0.379	
Chi square_bs(13)	23.281	baseline vs. saturated
p > chi square	0.028	
Population Error		
RMSEA	0.027	Root Mean Square Error of Approximation
90% CI, lowerbound	0.000	
, upperbound	0.139	
Pclose	0.623	RMSEA probability<= 0.05
Size of residuals SRMR	0.038	Standardized root mean squared residual

Source: Own elaboration based on Stata 14.

Once the goodness of fit of the model was determined, we examine the structural model results (Table 5). Based on Table 5, ICT use positively affects the SC activities (β=0.286) (hypothesis 1). Higher levels of ICT use shows citizens are more digitized and probably have better digital skills than the rest. As the ICT use is greater, citizens can perform smart cities activities. People with fewer ICT use will not be able to develop all kind of smart cities. For instance, citizens without smartphones are less likely to use parking apps or doing e-commerce.

Besides, trust on the website directly affects SC activities (hypothesis 3). Trust significantly and positively explains SC activities (β=0.06). Therefore, citizens with a higher level of trust on the website are more likely to buy products and contact local governments. This finding contradicts Vazquez and Vicente (2019) but is in line with most of the literature (Yeah, 2017; Hosmer, 1995). Furthermore, awareness of the smart city concept is a significant predictor of doing smart city activities (hypothesis 2, β=0.049). The more aware people are about the concept of smart city, the more prone they are to do smart activities. This result confirms previous literature in the subject (Yeh, 2017; Neirotti et al., 2014).

On the other side, labour condition and age are the two significant factors of ICT use. Citizens with a permanent occupation have a greater ICT use than the rest. Besides, the younger the citizen, the more likely he will use ICT more intensively. This result follows previous studies (Volmer et al., 2018, Yeh, 2017). Hence, young citizens with a permanent job will indirectly do smart activities.

Moreover, the education level is not a significant factor of ICT use, contrary to the literature review provided (Belanche et al., 2016; Kiiski and Pohjola, 2002; Hargittai, 1999). This result is not surprising considering the sample selection bias. It is likely that respondents of an online survey have more digital skills and education than the whole population. On the other side, gender is not a significant factor of ICT use or SC activities.

Table 6. Structural models

Variable	Structural equation SC Activities	Structural equation ICT use
ICT use	.2865806**	
Trust	.0063282**	
Awareness	.0492644 ns	
Education		-.0204209 ns
Labour_condition		.075872**
Age		-.0029159**
Gender		.0039698 ns

Source: Own elaboration.
Notes: ns means not significant; ** significant at 5% level.

5 Conclusion

The main contribution of this paper is to offer some highlights about the citizens' perception on smart cities in a city from a developing country as Argentina. In particular, the paper examines the determinants of smart cities activities across individuals from Argentina. Although there is some empirical literature on this subject in developed countries, much less research has been conducted in the developing world where infrastructure and technological conditions are different. The paper also provides some insights useful for city stakeholders and policy makers to design properly smart city policies and strategies for citizen engagement.

Based on the results obtained, local governments should focus attention on performing an ex-ante process to promote ICT use and bring trust to the web. This strategy will be useful to encourage activities or initiatives of smart city among citizens, especially young citizens and those having a permanent job. Moreover, this policy seems to be more significant than motivating citizens about the benefits and opportunities related to the smart city since awareness of smart cities is not a significant factor for encouraging SC activities. Public authorities should coordinate and cooperate

with civic associations to raise trust and facilitate the understanding of Smart Cities' initiatives and projects. This policy follows the international successful experience of global cities such as London, where citizens drive change in the same way as technocrats, business or policy makers.

Some limitations of the model are the omission of some variables such as Citizens' civil engagement; the sample size that is not large enough, and the sample selection bias, since the survey was conducted to followers of the municipality's social network. Therefore, results represent that population, and not the whole citizens of Bahía Blanca. It would be useful to reproduce the survey to other citizens' profiles. For instance, a survey conducted to citizens without internet access or use.

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Adecuada asignación de los recursos en sistemas de servucción bajo enfoque Lean Services: caso de estudio industria de la hospitalidad

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Resumen. Asignar recursos en épocas de crisis, más en tiempos de pandemia, se torna un problema prioritario en las organizaciones actualmente, caso de los sistemas de servucción, haciendo especificidad en la industria de la hospitalidad, en la cual la demanda es escaza o nula, lo que impacta de manera significativa su sostenibilidad debido a que afecta su productividad y su rentabilidad, es así que, urge implementar metodologías agiles que conlleven a una reorganización y/o definición de procesos para establecer así con la mejor asertividad los recursos que realmente se requieren en aras de responder de manera efectiva a los requerimientos del mercado actual. Teniendo en cuenta este planteamiento el presente trabajo describe la aplicación de una metodología denominada adecuada asignación de recursos en sistemas de servucción, sobre un caso de estudio particular de una organización de servicios de hospitalidad Categoría III, en la ciudad de Cartagena de Indias Colombia, la cual para el departamento de Bolívar represente el 70,3% del PIB y de este el 4,4% lo aporta Cartagena representado en actividad turística. Para el caso de Colombia para el 2020 se esperaba un incremento del 3,5 al 3,8% de aporte del turismo al PIB, pero no se logró debido al efecto Covid – 19. De manera general se observa una empresa que se equivoca en la definición de los recursos necesarios para actividades misionales comprometiendo la eficiencia y la calidad de su operación.

Keywords: Asignación de recursos, Lean Services; servucción, industria de la hospitalidad, Covid -19

Abstract. Allocating resources in times of crisis, more in times of the pandemic, becomes a priority problem in organizations today, in the case of service systems, making specificity in the hospitality industry, in which demand is low or void, which significantly impacts its sustainability because it affects its productivity and profitability, is that, it is urgent to implement agile methodologies that led to a reorganization and / or definition of processes to establish with the best assertiveness the resources that are really required in order to respond effectively to

the requirements of the current market. Taking into account this approach the present work describes the application of a methodology called adequate allocation of resources in service systems, on a particular case study of a Category III hospitality services organization, in the city of Cartagena de Indias Colombia, which for the bolivar department represents 70.3% of GDP and of this 4.4% is provided by Cartagena represented in tourist activity. For Colombia for 2020, an increase of 3.5 to 3.8% of tourism's contribution to GDP was expected, but was not achieved due to the Covid – 19 effect. In general, there is a company that is wrong to define the re-courses necessary for missionary activities by committing the efficiency and quality of its operation.

Keywords: Resource allocation, Lean Services; servuction, hospitality industry, Covid -19.

1. Introducción

Cuando de servucción se habla nos remitimos especialmente a aquellos sistemas productivos de altísima complejidad y variabilidad, dado sus características, que tienen como misión fundamental fabricar o prestar servicios (Garzón Sáenz, Solana Garzón, Ortiz Piedrahita, & Cogollo Sepúlveda, 2017), y que se fundamenta en la aplicación de un modelo gerencial que equipara la "producción" como fabricación del producto, con la "servucción" como la fabricación del servicio (Briceño de Gómez & García de Berrios, 2008). Dentro de estos podemos citar muchos ejemplos tales como: Restaurantes; Hoteles; Bares; Instituciones de Educación Superior; Centros Comerciales; Instituciones de Educación Media y Básica; Centros de Servicios de Salud; Clínicas y Hospitales desde baja complejidad hasta alta complejidad; Centros recreacionales, entre muchos otros que en la actualidad dinamizan la economía mundial convirtiéndose así en todas las naciones en la principal fuente de generación de empleo y de aportación al producto interno bruto de las mismas (Arellano Díaz, 2017).

En entrevista realizada a Nanno Mulder Jefe de la Unidad de Comercio Internacional de la División de Comercio Internacional e Integración de la Comisión Económica para América Latina y el Caribe (CEPAL), este establece que los servicios son, por lejos, el sector predominante de las economías de América Latina y el Caribe, representando el 70% del PIB y 62% del empleo total en 2015 (Schuster, 2018), hoy en día, los servicios representan alrededor de dos tercios del valor agregado total mundial, pero el camino hacia la economía de servicios no ha sido el mismo en todos los países. Las economías desarrolladas se han estado moviendo hacia los servicios de forma continua, y hoy en día son las economías más orientadas a los servicios en el mundo, generando un 75-80 % del valor añadido en los servicios. Los servicios no constituyen una proporción tan alta en las economías en desarrollo, a excepción de algunos pequeños países que se especializan en el turismo o en los servicios públicos. En los países del Caribe, el sector servicios llega a un 74 % del valor añadido (Aboal, y otros, 2015).

Para efectos de enfocar este documento, el mismo se direccionará hacia un eslabón de la servucción como lo es, la industria de la hospitalidad también conocida como industria hotelera la cual en términos generales se encarga de fabricar y ofertar servicios

de alojamiento temporal; alimentos y bebidas, recreación entre otros relacionados a turistas de índole local; nacional e internacional (Vásquez Gómez & Osorio García, 2016). El concepto de hospitalidad puede ser definido como un proceso ritual que invoca la protección de un turista nacional o extranjero bajo la dinámica de circulación material de la propia sociedad, por lo tanto, factible de ser comercializada. Los sectores que otorgan hospedaje son aquellos económicamente y políticamente en condiciones de dar dicha protección (Korstanje, 2010). La industria de la hospitalidad en la actualidad y desde tiempos remotos ha tenido un gran auge y crecimiento dado el gran desarrollo que se ha generado como consecuencia de la globalización, el cual es un proceso económico, tecnológico, social y cultural a escala mundial de los países capitalistas desarrollados fundamentalmente, que consiste en el crecimiento de la comunicación y la interdependencia de mercados, sociedades y culturas. Y se caracteriza por la integración de las economías nacionales dominadas por las empresas multinacionales y la libre circulación del capital industrial y financiero; el incremento de la conectividad humana expresada en el desarrollo del transporte y las telecomunicaciones; el auge de las redes sociales; y la integración política en bloques regionales y globales lo cual ha establecido la necesidad irrefutable sobre todo para los inversionistas de dormir fuera de casa en aras de gestionar sus potenciales inversiones (Meza Perez, Zaldivar Puig, & Fernandez, 2016). Lo anteriormente planteado en paises como el caso de Colombia y en especial como la ciudad de Cartagena de Indias la cual además de servir como epicentro turístico y hotelero dada su historia, hoy en día por su ubicación estratégica se ha convertido en punta de lanza para el comercio internacional, para el turismo de reuniones y otras derivaciones de esta (Bustillo Castillejo & De la Espriella Mendoza , 2013), lo que ha traído consigo la llegada a la misma de muchas personas de diversas nacionalidades a gestar cualquiera de las derivaciones de turismo existentes, Cartagena está preparada para recibir todo tipo de turismo: desde el vacacional hasta el de negocios. Su ocupación hotelera en 2018 fue del 66,6 por ciento y ese mismo año se convirtió en el segundo destino del país a donde llegan más extranjeros, después de Bogotá. Mientras que en 2008 Cartagena recibió alrededor de 567.000 viajeros en vuelos nacionales, en 2017 la cifra superó los 2 millones. Según el Dane, en 2016, La Heroica representaba el 70,03 por ciento del peso relativo del PIB de Bolívar y, de ese total, el turismo simbolizaba el 4,4 por ciento del departamento (Revista Semana, 2019) En cuanto a vuelos internacionales en 2017 la cifra fue de 328.483, que equivale a un incremento del 200% en los últimos diez años. Adicionalmente, en cruceros, durante 2009 la ciudad recibió más de 270 mil turistas en cruceros y para 2017 se registraron 338.172 según cifras Corpoturismo, el aumento fue del 25% (Cartagena como vamos, 2020).

Según el reporte provisional del DANE para 2016, la participación del turismo dentro del Producto Interno Bruto de Colombia representa el 1,9%, equivalente a más de 28 billones de pesos. Si hacemos una desagregación por departamentos, para Bolívar la rama de Hoteles, restaurantes, bares y similares representaron el 3,1% del PIB departamental en 2016. El DANE muestra a precios constantes que desde el año 2000 hasta 2016 se ha registrado un incremento de esta rama en Bolívar del 119%, pasó de 372 mil millones de pesos a 815 mil millones, es decir, un crecimiento promedio anual aproximado del 5% (Cartagena como vamos, 2020). Esto ha establecido la necesidad

de fortalecer la capacidad hotelera y como consecuencia se ha permitido el acceso de nuevas cadenas hoteleras o el fortalecimiento y renovación de las ya existentes en aras de mejorar su capacidad de hospedaje, impactando a los hoteles de pequeños y de mediano nivel los cuales han tenido que hacer esfuerzos por mantenerse a flote debido el carácter estacional de dicha industria (Garzón Sáenz, Ramos Franco, & Imitola Villa, , 2018), dado también los grandes rubros que se requieren para mantener en un buen nivel los servicios ofertados, además de esto en la actualidad esta industria se ha visto impactada de manera notoria por la proliferación del Covid -19 que ha establecido la necesidad de suspender actividades dado el alto riesgo que representa su funcionamiento debido a que los servicios en la industrial de la hospitalidad requieren alto nivel de contacto persona a personal, lo que ha traído como consecuencia el despido masivo de personal y la crisis económica de muchas por no decir la totalidad de las empresas del sector más en una ciudad como Cartagena donde como lo hemos descrito el turismo y en especial la industria de la hospitalidad juega un papel importante en el PIB de la ciudad y en la calidad de vida de sus habitantes (Asociación Española de Expertos Turísticos, 2020).

Según el informe especial de la CEPAL Como se describe en este mismo informe especial de la CEPAL, para el caso de América Latina y el Caribe, esta enfrenta la pandemia desde una posición más débil que la del resto del mundo. Antes de la pandemia, la CEPAL preveía que la región crecería un máximo del 1,3% en 2020. Sin embargo, los efectos de la crisis han llevado a cambiar esa previsión y pronosticar una caída del PIB de al menos un 1,8%. Sin embargo, no es de descartar que el desarrollo que la pandemia lleve a previsiones de contracciones de entre un 3% y un 4%, o incluso más (CEPAL, 2020).

Dado lo anterior y la importancia que representa la industria de la hospitalidad para el desarrollo mundial y local de la naciones y ciudades que la conforman se hace necesario adoptar medidas conducentes a mejorar el uso de los recursos requeridos para la operatividad de este tipo de contextos y hacerlos más productivos y rentables, lo que implica identificar que actividades o que aspectos no agregan valor el que hacer de dichas empresas para así determinar con la mayor exactitud posible que es necesario para garantizar servicios hoteleros de calidad durante la pandemia y una vez se salga de los efectos de la misma, surgiendo así como alternativa el Lean Services, con la cual se pretende la mejora en la eficiencia, velocidad de respuesta y flexibilidad en servucción de las empresas de servicios por medio de la administración basada en procesos y la eliminación de desperdicios, permitiendo así que tales organizaciones oferten diversidad de servicios al menor costo con altos niveles de productividad, rapidez en entrega, niveles mínimos de stock y óptima calidad (Arango Vásquez & Rojas López, 2018). Como lo describe (Gupta, Sharma, & Sunder M., 2016), aunque las organizaciones de servicios se tardaron en asimilar y usar la metodología Lean Services la cual es una derivación del Modelo Productivo Toyota (TPS), existen grandes retos en el uso de la misma por parte de los sistemas de servucción ya que un reto clave con los servicios es gestionar la intangibilidad de los residuos que surgen debido a la dificultad para identificarlos y a la presencia del cliente como coproductor. Otro desafío para aplicar Lean

en la industria de servicios es la falta de conciencia sobre los beneficios de implementar Lean en una organización de servicios como consecuencia del desconocimiento o inexperiencia en este tipo de metodologías con la cuenta los equipos que conforman a estas organizaciones y por otro lado como lo concluye (Hadid, Mansouri, & Gallear, 2016), Es necesario seguir trabajando para establecer una mejor planificación o secuenciación de la implementación del sistema lean. En aras principalmente de contribuir con el impacto directo de las prácticas de servicio lean en el rendimiento operativo y financiero de las empresas que conforman dicho contexto lo cual sustenta de buena manera el objetivo principal del presente estudio.

2. Metodología

Para el desarrollo del presente trabajo la metodología usada fue de tipo descriptiva, y se aplicó en un caso particular de una empresa que oferta servicios de hospitalidad de categoría 3, mediante entrevistas directas y mesas de trabajo en conjunto con la alta dirección de la misma, así como, con personal ejecutivo de alta confianza de las distintas funciones gerenciales, operativas y de soporte que en esta se desarrollan. Soportado en tres etapas así:

a) Diagnóstico empresarial basado en la metodología de empresa fuerte y sostenible diseñada por el equipo de consultores asociados a la gran alianza dentro del marco del proyecto de fortalecimiento al tejido empresarial, el cual se desarrolló en aquellas regiones donde Ecopetrol tiene operaciones en aras de fortalecer el tejido empresarial de dichas regiones.
b) Diagnostico especifico basado en la metodología de árbol lógico o árbol de problema.
c) Y finalmente se aplicó el paquete viable de soluciones (PVS), Denominado adecuada asignación de recursos en actividades misionales, con un énfasis en el análisis de la cadena de valor (VSM) con el propósito de identificar desperdicios o mudas en los eslabones que conforman la cadena de valor del sistema de servucción asociado a la industria de la hospitalidad intervenido y así establecer un plan de acción orientado a mejorar la productividad, la calidad y la rentabilidad de la organización.

3. Resultados

En este apartado describiremos cada una de las etapas desarrolladas para establecer la adecuada asignación de recursos en el sistema de servucción asociado a la industria de la hospitalidad intervenido y los resultados derivados de dicha aplicación.

3.1. Diagnóstico Empresarial.

El diagnóstico empresarial consistió en verificar el estado actual de la empresa en estudio, alrededor de 5 atributos definidos por el modelo de empresa fuerte y sostenible y

derivados del proyecto de fortalecimiento del tejido empresarial colombiano (ver Figura 1) (Unión Temporal Universidad Jorge Tadeo Lozano, E. C., 2013) que fue diseñado por el equipo de trabajo de la Unión Temporal, con el apoyo de Ecopetrol, Confecámaras y las Cámaras de Comercio. La firma Caso Consultores, experta en temas de negocio desarrolló y validó los instrumentos que componen esta herramienta (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas, 2013).



Figura 1. Modelo Empresa Fuerte y Sostenible

Para la construcción de esta metodología, se definieron los atributos (5 en total) que una empresa fuerte y sostenible debería tener, así como las características (29 en total) y las variables que los componen (172 en total). Este proceso tomó como referencias teóricas y metodológicas: el documento Enfoque a una metodología para la identificación de componentes que crean condiciones de durabilidad en las empresas colombianas (escrito por un grupo de investigadores de la Universidad del Rosario en Bogotá, encabezado por el Dr. Luis Fernando Restrepo Puerta), el Modelo de Excelencia para la Competitividad de la Corporación de Calidad y más de cien textos académicos y empresariales. Con esta base conceptual se identificaron las variables que pueden tener una organización y se analizó el nivel de causalidad entre ellas y sus relaciones, para ello se utilizó Matrix Vester como herramienta (ver figura 2), una herramienta de análisis que permite evaluar la influencia y dependencia de las variables que componen el sistema empresarial (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas., 2013).

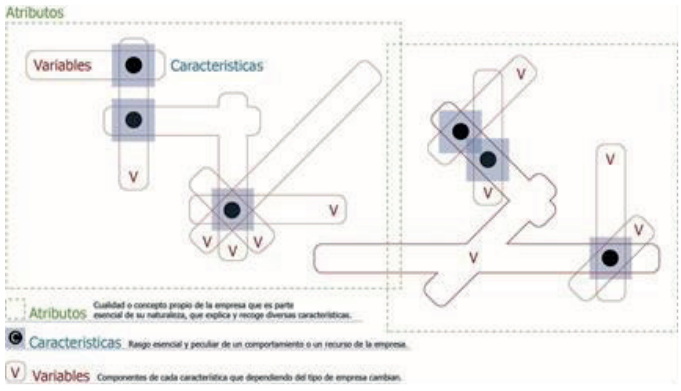

Figura 2: Relación de los atributos, características y variables.

El comportamiento de las variables se comparó con el comportamiento de 11 variables estudiadas en el mercado objetivo (que corresponde al que la empresa se encuentra actualmente, como en la que espera consolidarse en un periodo de 3 años), la aplicación de esta Metodología dio lugar al siguiente gráfico de radar (Ver Gráfico 3) (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas., 2013):

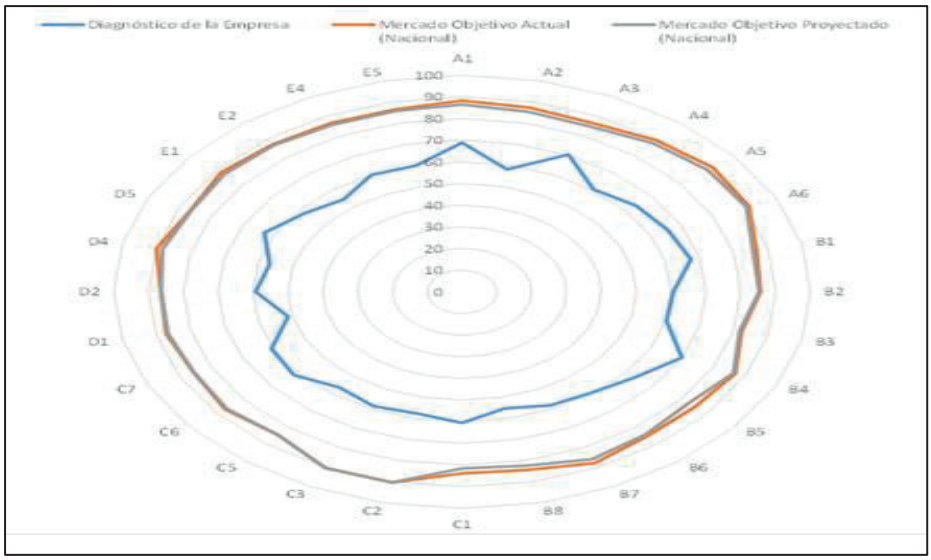

Figura 3: Resultado Diagnostico Empresarial

Como se puede ver en la Figura 3 y basado en el informe de diagnóstico empresarial (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas., 2013) y siendo coherentes con las características del sector hotelero de Cartagena y a nivel nacional, se observa una industria local y nacional muy dinámica, que está en constante evolución como resultado de la entrada de grandes cadenas hoteleras tanto a nivel nacional, como local, y hoteles boutique, que tienen una infraestructura física y tecnológica de última generación , así como una diversidad de servicios como alimentos y bebidas, recreación, lavandería, organización de eventos, ambientes confortables que garantizan una experiencia incomparable, además de personal en cantidad y con las habilidades necesarias y suficientes para satisfacer las necesidades de los turistas locales, nacionales y extranjeros de las más altas demandas, en comparación con una organización que muestra más de 30 años de existencia , posicionado a nivel local, que se evidencia en los grupos sociales de interés, muestra una infraestructura física y tecnológica, servicios como alimentos y bebidas, recreación y lavandería según su mercado actual, pero que, sin embargo, presenta grandes oportunidades de mejora, en torno a su

personal, su capacidad de generar valor, la generación de una verdadera ventaja competitiva que la diferencie competitivamente hablando y en términos de su responsabilidad social corporativa y en términos de su responsabilidad social corporativa. En consenso con el consejo de administración de la entidad y basado en el diagnóstico de negocio se determina como una importante oportunidad de mejora para hacer uso de una metodología que les permita gestionar adecuadamente sus recursos con el fin de fortalecer su trabajo y mejorar las brechas existentes entre su mercado actual y su mercado proyectado y descritos anteriormente.

3.2. Diagnostico Específico.

Como se señaló en el aspecto de la metodología una vez que se desarrolló el diagnóstico de negocio y se priorizaron las oportunidades de mejora, se aplicó un diagnóstico específico, haciendo un análisis basado en el árbol del problema, la herramienta de diagrama de Ishikawa, los 5 y el 5W - 2H (ver figura 4) y apoyado por la experiencia y el conocimiento en el tema de la hospitalidad por parte del consejo de la organización (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas. , 2013).

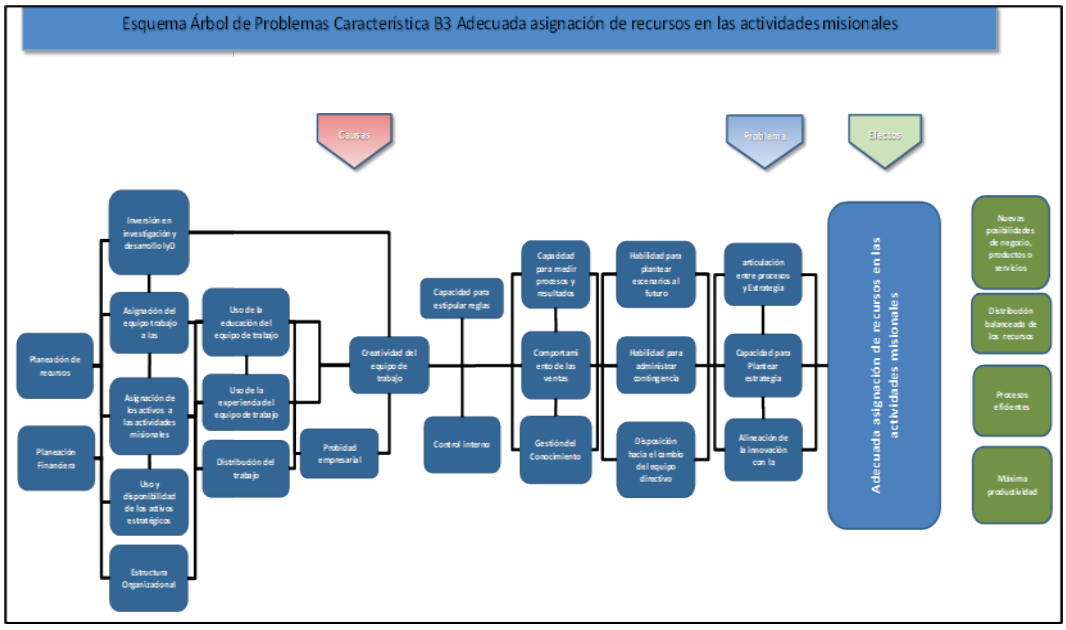

Figura 4. Árbol del Problema Maestro Para Diagnostico Especifico.

Derivado del análisis, desarrollado en conjunto con la alta directiva de la organización a partir de la metodología de lluvia de ideas y basado en el árbol de problema maestro,

se identificaron y priorizaron las siguientes oportunidades de mejora, divididas en causas y consecuencias derivadas de la misma.

Dentro de las causas establecidas en la mesa de trabajo conjunta con la junta directiva de la organización, se definen (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas., 2013):

- La planificación de los recursos es crucial para mejorar la eficiencia de las operaciones de la empresa, acortar el tiempo de entrega a los clientes y reducir los niveles de inventario, el desperdicio y la repetición del trabajo. Una asignación inadecuada de recursos afectará los resultados esperados por la empresa. En esta planificación, debe tenerse en cuenta una planificación financiera adecuada, que permita la ejecución de recursos para el desarrollo de actividades con la articulación de activos existentes y los necesarios para obtener los resultados esperados. Los recursos de investigación y desarrollo deben estar a la vanguardia del mercado.
- La empresa no puede cometer un error en la asignación del equipo de trabajo a las actividades de la misión, ya que comprometería la calidad de la operación, de esta manera es importante haber definido y alineado con la estrategia la estructura organizativa que permite identificar los activos estratégicos y el equipo definido a las actividades misioneras, ya que estas son las llamadas a ejecutar la actividad económica de la empresa. Por lo tanto, es importante medir cuánto la empresa toma el nivel de educación y experiencia del equipo de trabajo y pone a disposición el uso de activos estratégicos.
- Este equipo requiere un alto grado de identidad con la misión y los objetivos de la empresa, ya que tiene una influencia muy alta debido a su grado de experiencia, que debe ser decisiva en actuar con rectitud, honestidad e integridad. La empresa debe buscar un cambio de cultura, crear una actitud orientada al cliente y basada en procesos, para ser capaces así de adaptarse rápidamente a los cambios que le permitan abandonar las viejas estructuras o métodos de hacer las cosas.
- El propósito de distribuir los recursos siempre será obtener la máxima productividad posible de una combinación de activos.
- La asignación de recursos tiene como objetivo resolver qué empleo se dará a los diferentes factores de producción y qué cantidades de ellos se utilizarán en las diferentes actividades.
- La empresa debe ser capaz de medir de manera eficiente y eficaz sus procesos y resultados que la guíen para desarrollar las herramientas que permitan la reducción efectiva de costes, mejora de la producción, satisfacción del cliente, reducción de defectos y tiempo de ciclo y desarrollo de nuevos productos y servicios. Del mismo modo, desarrollar la capacidad de estipular reglas claras y efectivas del juego con métricas para identificar su cumplimiento. Los procesos deben tener métricas simples y deben compararse con una especificación.

Dentro de los efectos se identificaron (Unión Temporal Universidad Jorge Tadeo Lozano, Ecopetrol, Confecámaras, Asocajas., 2013):

- Identificar claramente la adecuación que se hace de los recursos a las actividades misioneras de la organización identificará claramente las acciones a desarrollar para asegurar la operación con los recursos mínimos que guíen a la empresa hacia el éxito sostenido con criterios de productividad, competitividad y sostenibilidad.
- El propósito de distribuir los recursos será siempre obtener la máxima productividad posible de una combinación de activos. Producir la mayor cantidad de bienes y/o servicios con el Mínimo de recursos.
- La asignación de recursos tiene como objetivo resolver qué empleo se dará a los diferentes factores de producción y qué cantidades de ellos se utilizarán en las diferentes actividades.
- El efecto que se obtendrá será dado por las nuevas posibilidades de negocio, productos o servicios, una distribución de recursos de forma más equilibrada y asistiendo a actividades misioneras, con procesos eficientes que lleven a la empresa a su máxima productividad.

A partir del diagnóstico específico, se determina la necesidad de planear e implementar una metodología que permita a la empresa definir sus procesos de manera adecuada, gestionarlos basados en objetivos y metas claras y poder destinar de manera eficiente y efectiva los recursos humanos, financieros, tecnológicos e infraestructuras, entre otros necesarios para ofertar una propuesta de valor competitivo en un contexto marcado por la globalización del sector , y por los efectos de una pandemia que ha debilitado la confianza del mercado objetivo actual y proyecta, lo que pone en riesgo la sostenibilidad y supervivencia del contexto en estudio.

Por lo tanto, se plantea la siguiente pregunta problemática: ¿Cómo contribuir con la mejora de la oferta de valor desde el punto de vista productivo a la organización objeto de estudio, ubicada en la ciudad desde Cartagena de Indias Colombia?

3.3. Análisis de la Cadena de Valor (VSM).

La mejor manera de entender el valor que ofrece un sistema de servucción, como es el caso del hotel, es a través del análisis de la cadena de valor; en el que, independientemente del tipo de actividad comercial a la que se dedica la organización, es capaz de generar satisfacción del cliente a través del valor recibido en el servicio. Una cadena de valor comprende toda la gama de actividades que se requieren para llevar un producto o servicio desde su concepción, a través de las diferentes fases de producción (que implican una combinación de transformación física e insumos de diversos servicios de producción) consumidor final y la disposición final después de su uso. El número de eslabones en cada cadena de valor varía según el tipo de industria (Ver figura 5) (Oddone & Padilla Perez, 2014).

Derivado del análisis de la cadena de valor actual de la organización estudiada, se puede inferir que:

• Se observa una organización que a pesar del tiempo de existencia de más de 30 años en el mercado local y poseer experiencia en el contexto, no funciona de manera armónica y sincronizada, como consecuencia de no tener implementado una gestión por procesos sino más de tipo funcional, lo que ha generado inestabilidad toda vez que no existe una clara definición de roles.

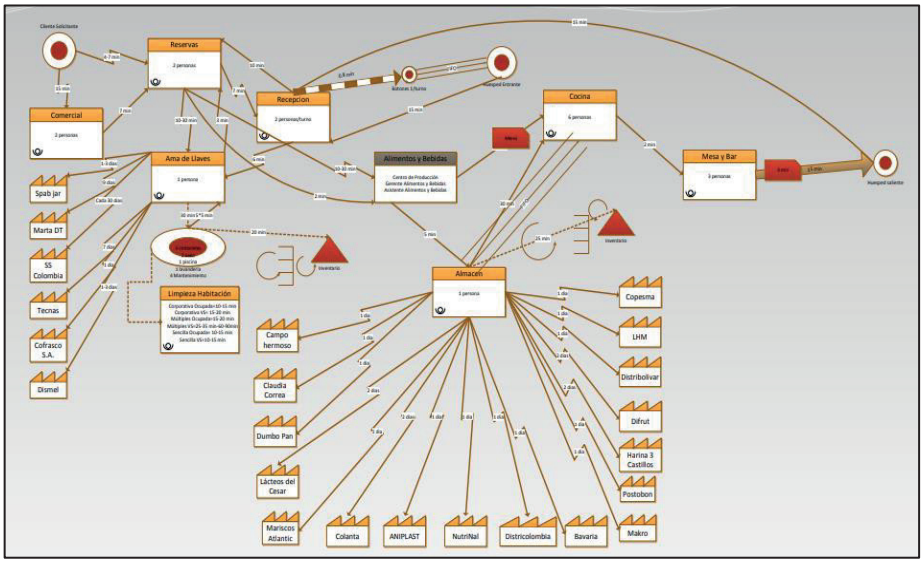

Figura 5. Mapa de la Cadena de Valor Actual Contexto Objeto de estudio.

- Se observa que al no existir roles definidos con claridad y en el afán de satisfacer y responder en el día a día con las necesidades del cliente el personal responsable de cada área desarrolla actividades de cualquier otra área abandonando sus responsabilidades generando así retraso en tareas propias y por consiguiente impactando de manera notoria en la gestión de la organización lo que sin lugar a dudas retrasa el desarrollo y adaptación de la organización ante los cambios y exigencias que establece el contexto de la industria de la hospitalidad.
- Al no tener un enfoque basado en procesos y enfocarse más hacia una estructura de tipo funcional, no se establecen tiempos tipo o tiempos estándar de servicio, lo que trae como consecuencia que algunas áreas tengan mayor asignación de recursos o basado en un análisis sistémico lo que muestra un despilfarro importante de recurso humano, así como también de recursos financieros lo cual afecta la sostenibilidad de la organización.

- A pesar de que, como organización hotelera típica se observa un ambiente agradable, espacios limpios y ordenados lo que da la impresión de tener implementado el concepto fabrica visual adecuada, operativamente hablando se percibe un ambiente laboral tenso y no armonioso como consecuencia de las múltiples tareas que deben realizar los actores y la administración tradicional que se implementa en la misma lo que muestra un alto nivel de desaprovechamiento de la experiencia del personal que en el hotel.
- Se establece a partir del análisis una organización que no basa su quehacer en hecho y datos, sino se basan en la experiencia de algunos de los miembros del equipo de trabajo, lo que dificulta la toma de decisiones asertiva y en los momentos oportunos creando así altos niveles de incertidumbre y mal uso y asignación de los recursos requeridos.

A partir de los análisis establecidos anteriormente y en conjunto con la alta dirección se determinó un plan de trabajo que llevo a definir la nueva cadena de valor y en aras de establecer de la mejor manera que recursos se requerían para ser una empresa fuerte y sostenible, así:

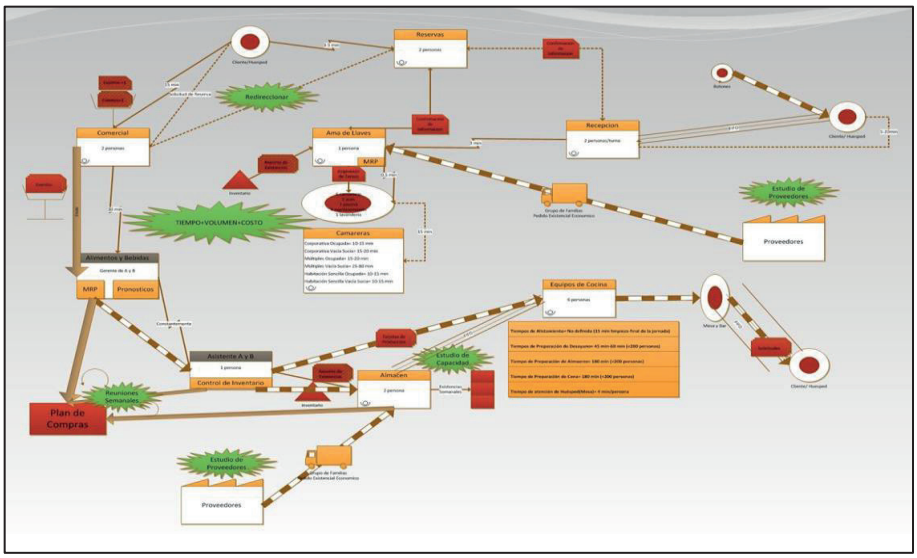

Figura 6. Mapa de la cadena de valor propuesto.

En la figura 6, se evidencia una propuesta de valor más simple, además de que se observa una secuencialidad en los procesos, lo que genera una adecuada sincronización, asignación de roles y responsabilidades.

Además de lo anteriormente planteado el definir de una manera clara los roles y responsabilidades permitió también definir qué personal se requiere, así como también la conformación de equipos de trabajos ajustados a perfiles y a la experiencia.

Al definir roles; responsabilidades y procesos se pudo establecer un sistema de medición del desempeño para la toma decisiones basada en hechos y en datos.

Y definitivamente se eliminaron despilfarros de recursos los cual estaba afectando de manera notorio la sostenibilidad de la organización.

4. Conclusiones

- Se observa un empresa que se equivoca en la definición de los recursos que se requieren para su operatividad, debido principalmente a que no cuentan con un enfoque de gestión basados en procesos, se basan mas en la experiencia de sus administradores en el sector que en hechos y datos y a que se maneja el concepto de polifuncionalidad, es decir, todos deben hace de todo en aras de garantizar el servicio y esto los ha llevado a tomar decisiones inadecuadas desde el punto de vista financiero lo que pone en riesgo la continuidad de la organización.
- Muchos de los resultados que se observan en la organización se deben en gran medida al empirismo y naturaleza formativa de la alta dirección, pero que mas sin embargo hoy les ha establecido la necesidad de mejorar y de apoyarse en personal con las habilidades necesarias para reinventar a la organización y mantenerla aun en estos momentos de crisis.
- Ante los eventos del Covid – 19, se puede establecer que la organización estudiada es altamente vulnerable y se ha visto bastante afectada, toda vez que se ha visto en la obligación de detener casi en su totalidad sus operaciones lo que ha implicado también eliminar puestos de trabajo. Pero en la medida que los efectos de la pandemia disminuyan deben determinar con la mayor exactitud posible los recursos requeridos para reinicio de operaciones de manera paulatina y además adaptar el sistema a la nueva forma de operar para garantizar el bienestar tanto de clientes internos como externos y devolver así la confianza y seguridad del mercado en el sector y estabilizarse rápidamente, lo que implica que deben contar con las tecnologías necesarias y el conocimiento pleno de sistema servuctivo para el logro de objetivos
- Dado el carácter de tipo estacional que muestra en términos generales el comportamiento de la demanda del contexto objeto de estudio, lo cual se puede traslapar a nivel de toda la industria de la hospitalidad tanto en Cartagena, como en el mundo se hace necesario que se establezca una cultura basada en hechos y datos lo que conlleva a generar un sistema de indicadores que permitan tomar decisiones de manera acertada y preparar a las organizaciones que conforman dicho sector para los momentos de alta demanda o los momentos

de baja demanda siempre pensando en el adecuado uso de los recursos tanto humanos, locativos como financieros siendo estos últimos altamente limitados en el tipo de empresas hoteleras citadas en el presente trabajo.

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Aportes del enfoque multimetodológico a la gestión de problemáticas derivadas del Covid-19. Avances para una intervención sistémica en grupos poblacionales

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Abstract. En este artículo se reporta un avance de la propuesta del uso combinado de una gama de métodos de Investigación Operativa (IO) clásica (*hard*) y métodos de estructuración de problemas (MEP o IO *soft*) en un marco multimetodológico, a fin de estudiar algunos aspectos de la complejidad organizacional y operativa generada a partir del Covid-19. Se presentan algunas etapas de *Soft System Methodology* (SSM), método de IO *soft*, combinado con programación lineal mixta, método de IO *hard*. anclándose éstos en un marco multimetodológico sobre una propuesta de Mingers y Brockelsby para la integración de metodologías.

Se presenta un avance sobre la aplicación del marco propuesto para asistir a la gestión general de dos grupos: personal de empresas y alumnos de una institución educativa. La aplicación puede reportar pautas para los tomadores de decisiones en un nivel operativo a fin de estructurar el problema y determinar el número de personal operativo o educativo teniendo en cuenta las restricciones de prevención ante la pandemia Covid-19.

El artículo contribuye al debate actual generado por la problemática del Covid-19, mediante la práctica de múltiples paradigmas y multimetodologías en IO y se alinea con la reciente tendencia a combinar métodos *hard* con métodos *soft* de IO.

Keywords: Covid-19**,** Multimetodologías, Investigación Operativa *Hard* y *Soft. Soft System Methodology,* Programación Lineal Mixta

1 Introducción

La sociedad se enfrenta cada día a una creciente complejidad y a una constante incertidumbre, motivados por el Covid-19, manifiestos en la progresiva gama de problemas que requieren permanente atención. Las ciencias organizacionales pueden amenguar estas situaciones desarrollando métodos y metodologías que ayudan a entender estas situaciones, mejorarlas y en algunos casos solucionar la continua variedad de problemas que se presentan. En particular, la IO puede contribuir a esta tarea ofreciendo una gama de métodos y técnicas para la ayuda en la toma de decisiones.

Hasta hace algunos años, la naturaleza de las aplicaciones de la IO se caracterizaba por el uso de una técnica, método o metodología en particular y también por alinearse a un determinado único paradigma, i.e.: *hard* (modelos matemáticos), *soft* (metodologías cualitativas) o critica. Sin embargo, en las últimas dos décadas, profesionales y consultores en IO han empezado a combinar métodos, metodologías y técnicas provenientes no solo de un paradigma sino de varios. A esta modalidad de IO se la llama práctica multimetodológica en un contexto multi paradigmático (MM). Hay evidencia en la literatura de IO que las MM han sido aplicadas en varios contextos organizacionales Mingers (1997a, b); Mingers (1999); Mingers (2001) Mingers and Munro (2002). Es interesante notar que esta práctica se circunscribe a todo tipo de organizaciones, incluyendo el contexto de pequeñas y medianas empresas (PYME), Castellini y Paucar-Caceres (2018), Paucar-Caceres, et al (2015), Castellini et al (2017), Pontelli et al (2014), Silva Barros et al (2013).

Es interesante ver que el marco conceptual más usado para argumentar y justificar el uso de metodologías de IO en modo multi metodológico ha sido el propuesto por Mingers y Brocklesby (MyB) (1997); este es un marco en la forma de una matriz en la cual las distintas metodologías a usarse están ubicadas en línea con su mejor utilidad en alguna de las cuatro fases de toda intervención: Apreciación; Análisis; Evaluación y Acción. Tomando como punto de partida esta matriz se propone, una gama de metodologías/métodos. Donde la propuesta aquí presentada es una contribución al contexto problemático actual y a la buena práctica multi metodológica en IO,

En resumen, en este artículo se presenta la matriz de MyB, dejando expresadas las metodologías propuestas para algunos de sus elementos. Se expone y reporta avances en grupos afectados por la pandemia. En estas intervenciones, un equipo de tres investigadores se propone trabajar virtualmente con personas de diferentes niveles de estos grupos directamente involucrados en la problemática. La intervención se desarrollará virtualmente usando y combinando metodologías de IO *soft* (o MEP), y herramientas de IO *hard,* con el objetivo de tomar medidas que prevengan los contagios de los grupos en estudio, así como la implementación de las mejoras propuestas en los procesos de gestión organizacional a nivel operativo.

El artículo está estructurado de la siguiente manera. Después de esta introducción, en la sección 2, se presentan los fundamentos teóricos, resumiendo brevemente el papel de las metodologías *soft* y *hard* en IO y la reciente práctica de MM. En la sección 3, se introduce el esquema/marco de MyB. En la sección 4 se describe con cierto detalle la propuesta de aplicación del esquema de MyB y se discuten los posibles resultados de la intervención. Finalmente en la sección 5 se esboza las conclusiones iniciales y se sugiere una agenda de futura investigación.

2 Fundamentos teóricos

Como se menciona en la introducción, la complejidad e incertidumbre que afronta la sociedad en general y las organizaciones en particular como consecuencia de la pandemia COVID-19, incide en múltiples aspectos, siendo quizás el más relevante la

posibilidad de contagio de las personas, lo que obliga a analizar la problemática con un enfoque sistémico.

Más aun cuando los problemas de gestión en las organizaciones, en general no están claramente definidos, no hay acuerdo entre los involucrados o stakeholders (personas de adentro o fuera de la organización que pueden afectar o ser afectados por esta situación), el interés no está necesariamente en encontrar el óptimo y sí en encontrar una solución de compromiso, como lo indican Mingers y White (2010). Es en estos casos cuando las metodologías IO *soft* han sido instrumentales en ayudar a mejorar la situación considerada problemática. En estas situaciones, un equipo de IO, conjuntamente con los stakeholders de la organización pueden trabajar en el análisis de la situación compleja y en la propuesta de un plan de acción, teniendo en cuenta los aspectos socioculturales (Yolles, 2010).

2.1. La multimetodología como práctica multi paradigmática en la IO

A principios de los 90, surgió un interesante debate en la IO y las comunidades de sistemas en torno a cuestiones relacionadas con el uso de más de una metodología (combinándolas o usando partes de ellas). Los académicos y los profesionales de sistemas han estado debatiendo las posibilidades de utilizar metodologías de diferentes paradigmas reconociendo las fortalezas y debilidades de las mismas.

Paucar-Caceres (2003 a y b) ilustra cómo aplicar estas diferentes metodologías provenientes de uno o de diferentes paradigmas; esto lo hace utilizando el marco propuesto por Mingers (1997a); Mingers y Brocklesby (1997). Las diversas metodologías propuestas en este trabajo no provienen de un solo paradigma sino de un abanico multiparadigmático; es decir se propone algunas metodologías o partes de ellas, del espectro *hard-soft*. La Fig. 1 ilustra estas opciones; la opción (3) es la que más se acerca al esquema que este artículo adopta.

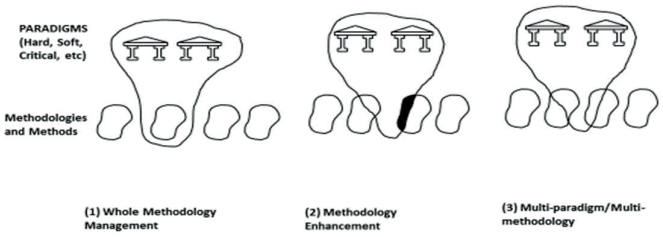

Fig.1. Intervención multimetodológica-multiparadigmática (de Mingers, 1997a)

2.2. La emergencia de los métodos de estructuración de problemas y la práctica multimetodológica

Los MEP, o IO *soft*, son aproximaciones basadas en modelos, que contribuyen de una manera constructiva y apropiada sino a la solución, al alivio de situaciones problemáticas complejas.

En general, estas metodologías cuestionan el paradigma de optimización basado en una epistemología positivista muy prevalente por muchas décadas en las ciencias de administración y se alinean más bien con un paradigma de aprendizaje y adhieren a una epistemología interpretativa y crítica. En otras palabras, son metodologías que se caracterizan por: estructurar los problemas, incorporar modelos conceptuales, considerar la subjetividad y trabajar para organizaciones, con activa participación de sus miembros, como se indica en Rosenhead (2006 y 1989), Rosenhead y Mingers, (2001), Vidal (2006).

Aun cuando en su aparición en los 80s, las metodologías IO *soft* o MEP se aplicaron en forma única e individual (SSM, SODA), como en Checkland (2000) y Eden y Ackermann (2004), en los últimos años, se han desarrollado aplicaciones con combinación entre ellas y han dado paso a la práctica de MM, en la cual IO *soft* y *hard* son aplicadas en conjunción, como puede verse en Ackermann y Eden (2011), Franco y Lord (2011), Georgiou (2012, 2008), Mingers (2000), Mingers y Gill (1997).

Esencialmente, como se explica con más detalle en la sección siguiente, la utilización de multimetodologías en un marco multi paradigmático (MM), es un área de la IO que se focaliza en la posibilidad de combinar diferentes métodos o parte de ellos, dentro de una intervención social particular, caracterizada por su complejidad, como puede verse en Henao y Franco (2016) y Small y Wainwright (2014)

Esta combinación se fundamenta en que: (a) Las situaciones problemáticas reales son multidimensionales, (b) Una intervención es un proceso llevado a cabo en etapas que tienen diferentes tareas y dificultades, que pueden ser mejor abordadas por diferentes métodos, (c) La combinación de métodos puede brindar nuevos puntos de vista y hacer más confiables los resultados.

Es un campo relativamente reciente en el que hay especial interés en los investigadores. Existen algunas publicaciones que han sido seminales y muy influyentes en el avance de esta práctica en varios foros de IO; una de ella que cabe destacar es el libro de Rosenhead y Mingers (2001) donde se analiza el mundo multidimensional, de acuerdo a la versión de Habermas (1970) (Acción, Verbalización, Emoción) en el que están incluidos los procesos de toma de decisión. Enfatizan el hecho de que se debe considerar toda intervención como proceso y analizan los aportes de cada uno de los métodos suaves cuando se utilizan de manera combinada con otros. Reseña las combinaciones *soft-soft* y *soft-hard* más utilizadas hasta ese momento. Así mismo otro artículo muy influyente ha sido el de MyB (1997) en el cual definen la terminología, las variedades de MM, el porqué de su uso, basado en la multidimensionalidad del mundo (personal, social, material), la intervención como proceso, la práctica y la factibilidad de las MM, basada en diferentes tipos de problemas: filosóficos, culturales y cognitivos, así como las dificultades que pueden surgir en su aplicación, dando un esquema de uso y sugiriendo cuál de ellas es apropiada para cada fase de intervención, lo que resume en diferentes figuras. Kotiadis y Mingers, (2006) enfatizan las limitaciones que pueden existir en el uso de las multimetodologías, citan algunos casos relevantes y explicitan un caso práctico que es la evaluación de un sistema social y de cuidados de salud, comentando la pertinencia de la multimetodología aplicada (*Discret Event Simulation* y SSM) y algunas de las dificultades encontradas.

3 Marco para posicionar distintas metodologías en la práctica multi metodológica/ multi paradigmática en IO Esquema de Mingers y Brocklesby (MyB)

En esta sección se describe sucintamente el marco desarrollado por MyB para posicionar las distintas metodologías de IO.

Como se ha expuesto en la sección anterior, el esquema planteado por MyB (1997) es el más usado para justificar y guiar la práctica multi metodológica y multi paradigmática en IO; particularmente cuando se trata de usar varias PSM en combinación.

La Tabla 1 ilustra el modo en que MyB encuadran y complementan los métodos o partes de métodos que fueron seleccionados. Este esquema contiene dos tipos de dimensiones a considerar: (1) las 4 fases de la intervención; éstas aparecen en el esquema de Mingers como 4 "As" (*Appreciation, Analysis, Assesment y Action*); y (2) tres dimensiones o mundos de Habermas, que aun cuando, en la práctica durante toda intervención, interactúan continuamente entre sí, en el esquema se las considera como discretas es decir separadas; esto para ayudar a explorar la complejidad de la situación problemática en consideración. Estas dimensiones son: *material, personal y social*. Las 4 'A's de MyB traducidas al castellano quedarían como *Apreciación; Análisis; Evaluación y Acciones* (**AAEA**).

Tabla 1. Marco para posicionar distintas metodologías en la práctica multi metodológica/ multi paradigmática en IO (MyB 1997)

Fases de la intervención multi metodológica (AAEA)				
Dimensión del problema	**Apreciación de características del problema en cuanto a:**	**Análisis de estructuras y restricciones en:**	**Evaluación de:**	**Acciones para:**
Social	prácticas sociales, relaciones de poder	distorsiones, conflictos, intereses	vías para cambiar las estructuras existentes	generar empoderamiento y alineamiento
Personal	creencias individuales, percepciones	diferencias entre las percepciones y las posturas racionales	Conceptualizaciones y construcciones alternativas	generar predisposición y consenso
Material	evidencias físicas	estructuras causales	alternativas físicas y estructurales	seleccionar e implementar alternativas adecuadas

Soft System Methodology (SSM), Checkland (1981), uno de los MEP más difundidos, combina los principios de sistemas de pensamiento con los puntos de vista individuales, reconociendo las diferentes percepciones de los problemas, e interpretándolas mediante modelos conceptuales, buscando como los sistemas podrían funcionar mejor.

Esta metodología, sobre la base de lo que se percibe como relevante, elabora conceptos abstractos que luego se interpondrán y cotejarán con el mundo real.

Los MEP requieren que el equipo de IO actúe no solo como analista, sino también como facilitador, esto es llevar a cabo la intervención juntamente con los involucrados, ayudando a estructurar y definir la naturaleza de la situación problemática y a fundamentar la evaluación de prioridades y el desarrollo de planes para la subsecuente implementación.

4 Propuesta de diseño e implementación de la Intervención Multi metodológica en dos poblaciones afectados por la pandemia

Partiendo de la premisa que todo estudio sistémico intenta aportar a la mejora de las situaciones problemáticas que se presentan en los procesos estratégicos y de gestión de todo tipo de organización, en el caso que nos ocupa, dos grupos afectados por la pandemia COVID-19, se considera necesario conocer no solo sus características, sino también el contexto en el que se encuentran. Es así que en esta sección se enumera medidas preventivas tomadas el contexto de la pandemia, para luego esbozar el diseño de la combinación de metodologías aplicadas y se reporta el avance en la ejecución del estudio.

4.1 Contexto

Medidas tomadas ante la problemática en CABA. Se han implementado medidas que pretenden disminuir la circulación de personas en el trasporte público y privado, evitando aglomeraciones y al mismo tiempo incentivando el comercio barrial.

Se restringió el uso del trasporte público exclusivamente a trabajadores esenciales y personas con permiso de circulación.

Como medida de control se dispusieron distintos centros de trasbordo, dinámicos y rotativos en los que se realizaron revisiones de síntomas y documentación necesaria y obligatoria para poder circular.

Se aumentaron las medidas y la frecuencia de los procesos de desinfección y limpieza, se establecieron protocolos y recomendaciones para asegurar una correcta higiene a nivel personal y conjunta, como por ejemplo el uso obligatorio de barbijos, marcas estipuladas para asegurar el distanciamiento social correspondiente, modalidad de viaje únicamente sentado dentro de los trasportes.

Como medidas de control se desarrollaron diversas aplicaciones como permisos de circulación que se adquieren vía web, el control de los permisos se realiza directamente desde la aplicación, se colocaron cámaras en patrulleros y cámaras detectoras de temperatura en los centros de trasbordo.

Con el objetivo de evitar aglomeraciones, se realizaron diferentes intervenciones para asegurar el distanciamiento social. Se establecieron ejes comerciales en los que se focalizó la apertura de ferias, comercios, peatonales extendidas, calles cerradas a la circulación de vehículos, veredas ampliadas, demarcaciones de distancia y prevención.

Para incentivar el comercio barrial, con el objetivo de reactivar la economía sin la necesidad de utilizar el trasporte público para recorrer grandes distancias, favorecer la movilidad peatonal y el uso de bicicletas. Los comercios deben respetar un protocolo que garantizan entre otras cosas, el uso obligatorio de barbijos tanto para el personal trabajador como para clientes, el uso de herramientas de marcación para asegurar la distancia mínima que se debe respetar dentro del establecimiento y fuera al formar filas, protocolos específicos en caso de detectar un caso sospechoso de Covid-19. Avaro et al (2020), Rodriguez Espinola et al (2020).

Algunas poblaciones involucradas. En esta fase de la cuarentena en el que cada sector de la población tiene distintos intereses, los grupos identificados y sus principales intereses, son los siguientes:

- Pequeños y medianos comerciantes, les interesa reabrir su negocio y evitar contagios en sus locales.
- Industrias no esenciales, les interesa reabrir su producción de manera segura.
- Personal de salud (trabajadores esenciales), les interesa poder realizar su trabajo minimizando el riesgo de contagio y evitar el colapso del sistema de salud.
- Industrias esenciales (logística, venta de alimentos, servicios públicos) les interesa garantizar el abastecimiento de insumos básicos a la población.
- Trabajadores esenciales (logística, venta de alimentos, servicios públicos) les interesa evitar los contagios, sin discontinuar el suministro a la población.
- Trabajadores no esenciales (artistas, gimnasios, hotelería, gastronomía, turismo), les interesa retomar la actividad laboral.
- Niños y adolescentes, les interesa realizar salidas recreativas
- Estudiantes con escasa o nula conectividad, les interesa retomar las clases presenciales
- Deportistas les interesa retomar su actividad física al aire libre en vía pública
- Deportistas de alto rendimiento, les interesa poder retomar su entrenamiento.
- Población de riesgo o adultos mayores, les interesa realizar salidas minimizando el riesgo de contagio
- Familiares de personas de riesgo o adultos mayores, les interesa minimizar el riesgo de contagio de su familia.
- Geriátricos y centros comunitarios, les interesa minimizar los riesgos de contagio en su entorno
- Barrios vulnerables y personas en situación de calle, les interesa minimizar los riesgos de contagio en su entorno
- Espacios culturales (bibliotecas, museos, iglesias, teatro), les interesa retomar la actividad.
- Transporte público, les interesa minimizar los riesgos de contagio, estableciendo reserva de asientos y mejorando la limpieza y desinfección
- Actores de los estados nacional, provincial y municipal

4.2 Diseño de la Intervención

Se seleccionaron tres de los grupos mencionados: industrias esenciales y no esenciales, y estudiantes con escasa o nula conectividad

El primer contacto es a través de representantes de los mismos que derivan en una investigación-acción desarrollada por el equipo de investigación interdisciplinario conjuntamente con los *stakeholders* de las respectivas poblaciones.

El objetivo de esta investigación-acción es proponer mejoras a las situaciones problemáticas de gestión planteados por los *stakeholders*, generadas por la pandemia. Para ello se prioriza el trabajo interactivo. Se propone una combinación de metodologías, de las áreas de IO *soft* y *hard*, considerando su potencialidad para proveer mejoras en los diferentes aspectos requeridos por las organizaciones.

Se indica en la Tabla 2. resaltado, el avance del trabajo de campo propuesto.

Tabla 2. Distintas metodologías propuestas en la práctica multi metodológica/ multi paradigmática en IO (MyB 1997)

Fases de la intervención multi metodológica (AAEA)				
Dimensión del problema	**Apreciación de características del problema en cuanto a:**	**Análisis de estructuras y restricciones en:**	**Evaluación de:**	**Acciones para:**
Social	prácticas sociales, relaciones de poder	distorsiones, conflictos, intereses	vías para cambiar las estructuras existentes	generar empoderamiento y alineamiento
	Workshop virtual			
Personal	creencias individuales, percepciones	diferencias entre las percepciones y las posturas racionales	Conceptualizaciones y construcciones alternativas	generar predisposición y consenso
	Entrevistas virtuales	**SSM**	**SSM**	
Material	evidencias físicas	estructuras causales	alternativas físicas y estructurales	seleccionar e implementar alternativas adecuadas
	Visitas de campo virtuales		**Programación Lineal**	**Programación Lineal**

Usando el esquema MyB se sitúa algunas de las metodologías que se consideran adecuadas y relevantes en cada una de las dimensiones y fases. En la Tabla 2, se resumen algunas de las diferentes herramientas y metodologías (o partes de ellos) propuestos para ser aplicados a cada dimensión y fase de la intervención multi metodológica.

Considerando las 4 fases (columnas de la matriz de MyB).

Se presentan los avances realizados en las diferentes fases, en base al esquema original de MyB, resaltados en la Tabla 2.

Fase 1: Apreciación de las características del problema desde las dimensiones social, personal y material. Se propone un workshop virtual a organizaciones representativas de los grupos seleccionados. En esta 1ª etapa se efectúa un diagnóstico general de las organizaciones a fin de definir las situaciones problemáticas, de gestión, a ser abordadas. Se busca la participación de los involucrados claves, ya sea porque tienen el poder de tomar decisiones sobre el problema tratado o porque están directamente afectados por las decisiones a tomar. A partir de éstos, se elaboran en conjunto las figuras ricas (parte del método SSM de Checkland) de la situación considerada problemática, Fig. 2 y 3.

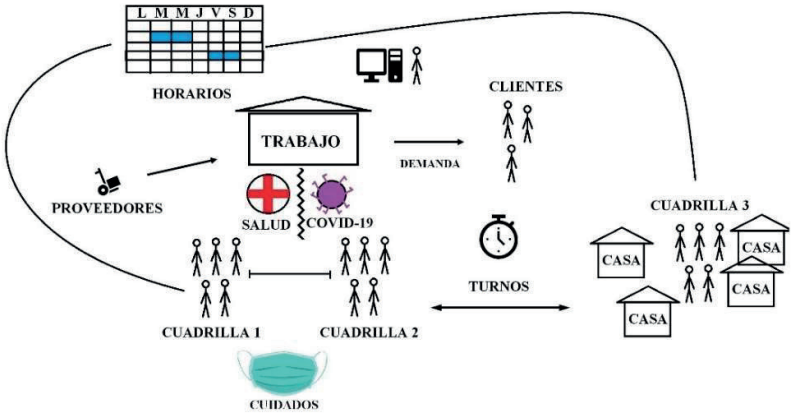

Fig. 2. Figura Rica (*Rich Picture*) de la Situación Problemática en la Industria

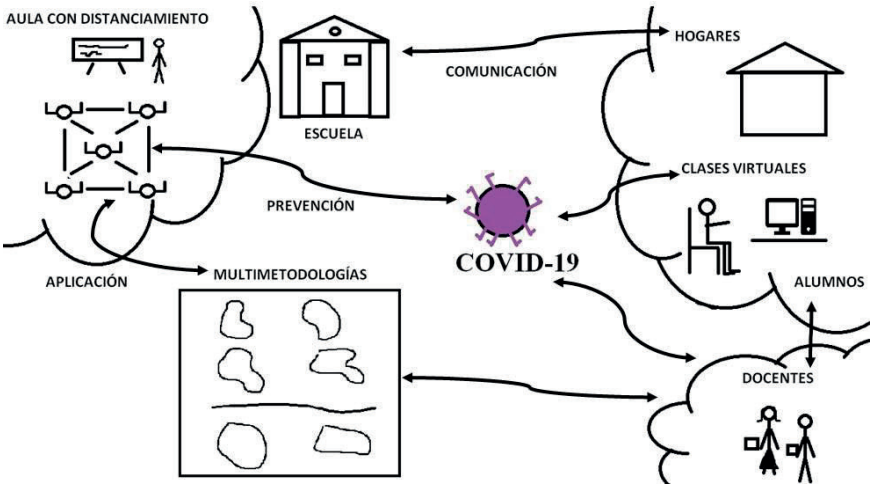

Fig. 3. Figura Rica (*Rich Picture*) de la Situación Problemática en la Institución educativa

Fase 2: Análisis de estructuras y restricciones. En esta segunda etapa se busca estructurar el problema. Analizando la figura rica, se pueden identificar las situaciones problemáticas, en un proceso participativo entre los miembros de la organización y el equipo. Se propone elaborar las correspondientes definiciones raíz (parte del método SSM de Checkland).

Fase 3: Valoración/Comparación. En esta etapa se priorizan y analizan las situaciones problemáticas. se propone realizar en la dimensión Personal y Social el Análisis 1,2,3 de SSM.

Fase 4: Definición de acciones para mejorar la situación problemática. La situación problemática se puede trabajar a diferentes niveles de las organizaciones. Para definir las acciones, en la dimensión material se propone aplicar Programación Lineal Mixta. Se presentan los programas lineales planteados para ambos grupos

Asignación de turnos laborales. En distintas actividades comerciales se tienen trabajadores asignados en diversos turnos, los cuales fueron pensados y diagramados bajo una lógica pre-pandemia. Por lo cual, existe una importante posibilidad de readecuación de los mismos mediante modelos de programación lineal mixta, de amplio uso en la programación de turnos de trabajo (JÖzder, Özcan, & Eren, 2020).

El modelo propuesto es aplicable a la actividad productiva esencial y no esencial, y se enfoca en el cuidado de las personas y minimizando la probabilidad de contagios en el ámbito laboral. La realidad de cada organización puede variar, pero se pueden esbozar una serie de lineamientos generales. La organización cuenta con *n* trabajadores y ofrece *l* tipos distintos de productos.

Se definen las siguientes variables:

$$X_{ih} = \begin{cases} 1 & \text{una persona } i \text{ trabaja en el horario } h \\ 0 & \text{una persona } i \text{ no trabaja en el horario } h \end{cases}$$

$$Y_{ij} = \begin{cases} 1 & \text{si las personas } i \text{ y } j \text{ forman parte de la misma cuadrilla} \\ 0 & \text{si las personas } i \text{ y } j \text{ no forman parte de la misma cuadrilla} \end{cases}$$

$$Z_{ijh} = \begin{cases} 1 & \text{si las personas } i \text{ y } j \text{ trabajan juntas en el horario } h \\ 0 & \text{si las personas } i \text{ y } j \text{ no trabajan juntas en el horario } h \end{cases}$$

$$P_{ph}: \text{cantidad de un producto o servicio } p \text{ a ofrecer en la hora } h$$

El problema se plantea en unidades de tiempo de horas $h \in H$ donde H representa el horizonte de planificación que pueden ser semanas, meses, trimestres, totalizando una cantidad *m* de horas. En este marco temporal se busca minimizar la exposición del personal, según la siguiente función objetivo:

$$min \sum_{i=1}^{i=n-1} \sum_{j=i+1}^{j=n} \sum_{h=1}^{h=m} Z_{ijh}$$

Se asume que se cuentan con los siguientes datos:

$Minh_i$:cantidad mínima de horas de trabajo de una persona *i* durante H

$Maxh_i$:cantidad máxima de horas de trabajo de una persona *i* durante H

D_{ph}:Demanda del producto o servicio *p* a la hora *h*

T_p:Tiempo de producción o de servicio *p*

LL_i:Duración máxima de la jornada de trabajo de la persona *i*
LC_i:Duración mínima de la jornada de trabajo de la persona *i*
P_p:cantidad de un producto o servicio *p* a ofrecer

Para terminar de conformar el modelo se establecen las restricciones que relacionan las variables entre sí, primero determinar si dos personas i y j trabajan en el mismo horario

$$2.Z_{ijh} \leq X_{ih} + X_{jh} \leq Z_{ijh} + 1 \quad \forall h,i,j \text{ con } i \neq j \tag{1}$$

Se trabaja bajo la premisa de generar turnos de cuadrillas estables, de manera de haber una persona con COVID positivo solo haya estado en contacto con su cuadrilla correspondiente y no haya posibilidad de contagio cruzado con el resto de la organización. Por eso se agrega la restricción de que si dos personas en algún momento trabajan juntas pertenecen a la misma cuadrilla:

$$Y_{ij} \leq \sum_{h=1}^{h=m} Z_{ijh} \leq m.Y_{ij} \quad \forall i,j \text{ con } i \neq j \tag{2}$$

El concepto de cuadrilla estable considera que si una persona i trabaja junto a una j, una tercer persona k trabaja con ambas o no trabaja con ninguna.

$$Y_{ij} + Y_{ik} \leq Y_{jk} + 1 \quad \forall i,j,k \text{ con } i \neq j \neq k \tag{3}$$

$$Y_{ij} + Y_{jk} \leq Y_{ik} + 1 \quad \forall i,j,k \text{ con } i \neq j \neq k \tag{4}$$

$$Y_{ik} + Y_{jk} \leq Y_{ij} + 1 \quad \forall i,j,k \text{ con } i \neq j \neq k \tag{5}$$

Es importante considerar que dependiendo de la persona se tiene la cantidad de horas máximas y mínimas que deberá trabajar dentro del horizonte de tiempo H.

$$\sum_{h=1}^{h=m} X_{ih} \geq Minh_i \quad \forall i \tag{6}$$

$$\sum_{h=1}^{h=m} X_{ih} \leq Maxh_i \quad \forall i \tag{7}$$

En el caso de personal dentro de la categoría de riesgo, se le debe dar de manera automática licencia médica con pleno goce de sus garantías laborales, asignándole $Minh_i = Maxh_i = 0$.

A su vez, se debe restringir la cantidad de horas que trabaja una persona de corrido:

$$\sum_{h=t}^{h=t+LL_i+1} X_{ih} \leq LL_i \quad \forall i,t < m - LL_i \tag{8}$$

$$LC_i.(X_{ih+1} - X_{ih}) \leq \sum_{h=t}^{h=t+LC_i} X_{ih} \; X_{ih} \leq LC_i \quad \forall i < n, t < m - LC_i + 1 \tag{9}$$

Finalmente es necesario establecer los niveles de producción horaria para satisfacer la demanda estimada.

$$\sum_{p=1}^{p=l} T_p.P_{ph} \geq \sum_{i=1}^{i=n} X_{ih} \quad \forall h \tag{10}$$

$$D_{ph} \leq P_{ph} \;\; con \; D_{ph} \geq 0 \; y \;\; P_{ph} \geq 0 \tag{11}$$

Este tipo de modelos, sirven de referencia general, sin embargo se podrían complejizar con la inclusión de flujos de stocks en el caso que se esté trabajando con productos, la apertura por especialidad necesaria del trabajador a la hora de realizar una tarea (Niknafs, Denzinger, & Ruhe, 2013), o una programación más formal de los tiempos de descanso (William S. Brownell, 1976) por mencionar algunos de los agregados posibles.

Asignación de aulas para la vuelta a clases. Se propone un modelo de asignación de alumnos a clases para asistir de manera presencial a la Institución al menos dos días a la semana, teniendo en cuenta la cantidad de alumnos total por curso y la ocupación máxima de asientos dentro del contexto de la pandemia COVID-19, tomando como hipótesis que el resto de los días los alumnos continuarán con sus clases de forma virtual.

Se definen las siguientes variables:

$$X_{ija} = \begin{cases} 1 \text{ un alumno i es asignado al día j por semana y al aula a} \\ 0 \text{ un alumno i no es asignado al día por semana j y al aula a} \end{cases}$$

$$Y_{ii'j} = \begin{cases} 1 \text{ si los alumnos i e i' concurren el mismo día j a clase} \\ 0 \text{ si los alumnos i e i' no concurren el mismo día j a clase} \end{cases}$$

A_a: *cantidad de* m^2 *del aula a*
DS: cantidad de m^2*/persona recomendados*
C: Coeficiente de beneficio extra de alinear horarios de hermanos
CDS: cantidad de días por semana que asisten los alumnos

Función objetivo:

$$max \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} \sum_{a=1}^{a=l} X_{ija} + C \sum_{i=1}^{i=n-1} \sum_{i'=i+1}^{i'=n} \sum_{j=1}^{j=m} Y_{ii'j}$$

Teniendo en cuenta:

1. Cada alumno debe asistir a la institución una cantidad de días determinado a la semana.

$$\sum_{j=1}^{j=m} \sum_{a=1}^{a=l} X_{ija} = CDS \ \forall i \quad (1)$$

2. Para evitar la circulación y el contagio por superficies, el día que un alumno concurre al colegio lo hará sin cambiar de aula.

$$\sum_{a=1}^{a=l} X_{ija} = 1 \quad \forall \ i,j \quad (2)$$

3. Se deberá respetar la distancia social, por lo cual cada aula tendrá una capacidad máxima de personas a respetar según su superficie total.

$$DS. \sum_{i=1}^{i=n} X_{ija} \leq A_a \quad \forall j,a \quad (3)$$

4. Por cuestiones pedagógicas, y para evitar rotación entre los alumnos, se prefiere que en un día *j* y un aula *a* estén siempre compañeros del mismo curso. Dado un alumno

o perteneciente al conjunto E_c compuesto por los alumnos de un mismo curso, y un conjunto E'_c con los alumnos o' pertenecientes a los cursos restantes.

$$X_{oja}+X_{o'ja}\leq 1 \quad \forall j,a \tag{4}$$

5. Puede existir una ponderación para que determinados alumnos que tengan hermanos en la misma circunstancia asistan determinados días a la Institución. Donde (i,i') constituye un par de hermanos.

$$2.Y_{ii'j} \leq \sum_{a=1}^{u=1} X_{ija} + \sum_{a=1}^{u=1} X_{i'ja} \leq Y_{ii'j} + 1 \quad \forall j,(i,i')con\ i\neq i' \tag{5}$$

Por un lado esto implica un beneficio en términos de la comodidad familiar, pero desde un punto de vista epidemiológico el contagio dentro de un mismo hogar es altamente probable (Merino & Díaz,2020), así que al considerar este factor se logra minimizar la posibilidad de contagios de un día *j* a otro. El peso de esta política en el modelo dependerá del valor que tome C en la función objetivo, se recomienda que C>1.

5. Conclusiones y futuras investigaciones

En este artículo se ha argumentado que la tendencia en la actualidad en el campo de la IO es el uso de varias metodologías, métodos y técnicas en combinación conjunta. El artículo revisa brevemente la historia de las metodologías *soft* en IO. Usando como base el esquema de MyB, el artículo reporta las propuestas iniciales de una intervención sistémica efectuada en dos tipos de organizaciones, una productiva y una educativa.
Es interesante destacar la potencialidad del enfoque sistémico, pudiendo detectarse diferentes situaciones a mejorar, así como las causas que las ocasionan. Al momento se presenta la estructura de referencia en el marco de la matriz de MyB y los avances en el uso de partes de la metodología SSM y la modelización de la P L Mixta para optimizar el número de personas involucradas, bajo las restricciones que impone la situación pandémica.
El enfoque sistémico, con participación más activa de los *stakeholders*, permite relacionar las diferentes situaciones problemáticas (figura rica) detectadas, en las diferentes dimensiones planteadas por MyB y definir planes de acción para modificar las causas que las generan. Esto se potencia, por cuanto una misma causa, puede incidir en más de una situación problemática.
El uso de herramientas de fácil comprensión para los involucrados (figura rica de SSM por ejemplo), aumenta las posibilidades de darle continuidad a la propuesta y de que la misma organización pueda continuar el esquema de mejora sin el acompañamiento del equipo de investigación.
Este es un proyecto en ejecución y el siguiente paso es avanzar virtualmente en el trabajo de campo.

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Modelo multicritério de apoio a tomada de decisão, baseado em Sistema de Informação Geográfico, para a gestão de acidentes de trânsito

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Resumo. Nas últimas décadas, devido a uma explosão do crescimento demográfico das cidades e, respectivamente, de suas frotas de veículos, a violência no trânsito vem crescendo gradativamente. De acordo com a Organização Mundial da Saúde, cerca de 1,35 milhão de pessoas são vítimas fatais todos os anos. No ano de 2017, a OMS classificou o Brasil como o terceiro país em número de acidentes fatais de trânsito. Com exceção dos grandes centros urbanos, as cidades emergentes, de médio porte, enfrentam certas dificuldades na gestão do trânsito local. Com base nessa problemática, as ferramentas de apoio à decisão multicritério e os sistemas de informação geográfica (SIGs) podem apoiar o processo de tomada de decisão. Neste contexto, é proposto um modelo multicritério para tomada de decisão para classificar as vias da cidade referente a quanto estas são críticas para a segurança da população. É proposta a utilização do método PROMSORT, para classificação, e os resultados são representados em SIG. É apresentada uma aplicação numérica para o caso da cidade de Mossoró/RN, avaliando-se as vias e provendo informação para a tomada de decisão dos gestores públicos.

Palavras-chave: Métodos multicritérios de apoio à decisão, Sistema de Informação Geográfica, Acidentes de Trânsito.

1 Introdução

A frota brasileira tem crescido em ritmo acelerado nas últimas décadas. Mortaire e Euzébio [1] citam que, entre 1999 e 2009, a quantidade de veículos no Brasil cresceu de 27,1 para 55,9 milhões. No período compreendido entre 2003 e 2014, segundo Carvalho e Rabetti [2], a venda de automóveis cresceu 102,6% ao passo que a de motocicletas cresceu incríveis 269,8%. Com tantos veículos circulando diariamente pelo país, pode-se notar também um número substancial de acidentes. De acordo Almeida, et al. [3], os acidentes de trânsito no Brasil se mantém como um importante problema de saúde e demandam diferentes abordagens em ações de prevenção. Além do custo social ser elevado, esses acidentes impactam diretamente na economia nacional, sendo a causa direta dos elevados custos demandados pelo Sistema Único de Saúde, resultando, apenas entre 2010 e 2015, em mais de R$ 1,3 bilhão gastos em atendimentos. [4;5;6]

Em 2017, a Organização Mundial da Saúde (OMS) considerou que o Brasil era o terceiro país com o maior número de óbitos provocados por acidente de trânsito. Essa situação ainda é agravada devido a inexistência de ferramentas e metodologias que permitam uma intervenção efetiva. Uma análise puramente numérica pode permitir um *insight* do panorama geral da situação, mas há uma série de outras variáveis, como por exemplo características físicas da via, ou mesmo comportamentais dos condutores a serem consideradas para uma análise mais precisa. Desta forma, uma simples análise de quantitativo de acidentes pode enviesar a análise por parte do gestor, podendo levar a decisões ineficazes. Neste contexto, os métodos de apoio à decisão multicritério podem prestar suporte a este processo.

No campo das ferramentas de apoio à decisão destacam-se as abordagens multicritério, que ganham cada vez mais atenção pela sua robustez e por facilitar a análise de casos mais complexos. Segundo Vincke [7], o apoio multicritério à decisão tem por objetivo dar ao tomador de decisão ferramentas para possibilitar-lhe avanços na solução de problemas de decisão onde diversos, muitas vezes contraditórios, pontos de vista devem ser levados em consideração. O autor agrupa os métodos em três classes. (1) Métodos de critério único de síntese, vindo da Escola Americana, onde o desempenho de cada alternativa em um determinado conjunto de critérios é levado em conta para a criação de uma pontuação, cujo resultado representará o quão bem avaliadas são as alternativas. Podemos citar como exemplo dessa família, além do próprio MAUT, o SMARTS, TOPSIS e AHP. (2) Métodos de sobreclassificação, que adota uma comparação de alternativas par-a-par para definir qual delas é melhor que as demais em determinado critério. Expoentes dessa família são o PROMETHEE e o ELECTRE. (3) Métodos Interativos, que unem a preferência do decisor à uma base matemática, e assim, de maneira interativa e sucessiva, as reavaliam até que convirjam em um resultado. Nessa classe, temos como exemplos os métodos STEM, TRIMAP e Pareto Race.

Os Sistemas de Informações Geográficas (SIGs), por sua vez, unem conhecimentos da Estatística, Cartografia e Geografia na análise de dados espaciais [8]. Segundo Simões e Bastos [9], um SIG é definido como uma ferramenta de coleta, armazenamento, processamento, análise e disponibilização de informações georreferenciadas, que asseguram maior facilidade, segurança e agilidade nas atividades humanas no que diz respeito ao estudo do espaço geográfico. São ferramentas capazes de desempenhar um estudo de campo de modo a obter dados de um determinado espaço e, desse modo, incorporá-los a um sistema topográfico de mapeamento [10]. Sendo assim, a utilização de SIGs desenvolve uma estratégia de estudo promissora ao apoiar o processo de tomada de decisão, possibilitando a visualização geográfica de dados referentes à região analisada.

Diante do contexto apresentado, este artigo propõe um modelo multicritério de apoio à tomada de decisão que, utilizando representação geográfica, pode prestar suporte ao processo de gestão do trânsito em um município, permitindo uma tomada de decisão mais ampla. Além disso, a representação geográfica dos resultados obtidos pode produzir importantes *insights* para os gestores, que podem visualizar o relacionamento que pode existir entre as diversas variáveis que influenciam nesse processo. Ao levarem em consideração variáveis qualitativas ou quantitativas, permitem uma avaliação mais completa do problema, podendo fornecer direcionamentos para a gestão, permitindo uma aplicação dos recursos públicos muito

mais efetiva. A utilização de um SIG, por sua vez, pode complementar o processo de apoio à decisão, trazendo uma visão geográfica e possibilitando uma visualização de dados mais conectada com a realidade dos gestores do trânsito urbano.

O modelo proposto foi aplicado para o caso da cidade de Mossoró/RN, possibilitando a classificação das vias da cidade quanto à criticidade. Desta forma, o gestor de trânsito pode visualizar quais áreas da cidade demandam mais atenção ou, até mesmo, atuação imediata. Este artigo é composto por dizer seções: Na seção 2 é realizado um panorama sobre o problema dos acidentes de trânsito no Brasil, destacando o caso da cidade de Mossoró/RN. Na seção 3, o método desta pesquisa é apresentado, assim como o modelo multicritério proposto. Na seção 4 é desenvolvida a aplicação numérica e apresentação de resultados obtidos. Na seção 5, os comentários e análises finais são enunciados. E na seção 6, as referências bibliográficas utilizadas.

2 Acidentes de trânsito no Brasil

As estatísticas a respeito dos acidentes de trânsito em todo o mundo têm fomentado o debate nos últimos anos ao apontar esse tipo de acidentalidade como uma das principais causas de óbito anualmente. Visando a diminuição substancial dessas mortes, de aproximadamente 1,35 milhão por ano [11] , a Organização das Nações Unidas lançou, em maio de 2011, a proposta da Década de Ação pela Segurança no Trânsito, compreendendo o período entre 2011 e 2020. Para essa proposta, diversas autoridades governamentais assumiram o compromisso de adotar medidas para fortalecer a capacidade de gerenciamento da segurança rodoviária, bem como também melhorar a segurança e comportamento dos condutores [12], uma vez que são registrados de 20 a 50 milhões de acidentes em todo o mundo a cada ano [11].

A nível nacional, Waiselfisz [13] aponta que foram registrados no Brasil 960.635 óbitos por acidentes de trânsito entre 1981 e 2011. Neste período, foi avaliado um aumento de 122% no número de óbitos registrados e 39,75% na taxa de mortalidade a cada cem mil habitantes. Segundo a ONU Brasil [14], a taxa de óbitos no ano de 2019 aumentou em relação ao ano anterior, apresentando um índice de 19,7 mortes a cada cem mil habitantes. Tal índice superou o valor da média obtida para a região do Cone Sul, estimado em 18,4 mortes, e até mesmo a média para toda a região das Américas, estimado em 15,6 mortes a cada cem mil habitantes.

A Organização Mundial da Saúde estima que, apesar de concentrarem pouco mais da metade da frota mundial, os países de baixa e média renda correspondem, sozinhos, por 93% dos acidentes fatais, e que estes acidentes custam aos países cerca de 3% do seu Produto Interno Bruto [15]. A nível nacional, segundo o IPEA [16], no ano de 2014 foram registradas 167.247 acidentes nas rodovias federais, estaduais e municipais e nas áreas urbanas no Brasil, representando um custo anual de R$ 56 bilhões, incluindo atendimento médico-hospitalar, seguros de veículos, danos a infraestruturas públicas, dentre outras despesas. Desse valor, constatou-se 6.743 acidentes fatais, representando um custo anual de R$4,5 bilhões.

Quando analisa-se a cidade Mossoró, no interior do Rio Grande do Norte, as informações ficam mais escassas. Sabe-se, de acordo com as estatísticas oficiais dos órgãos de trânsito e saúde do município que morrem cerca de 60 pessoas por ano. Segundo Bezerra [17], a cidade registrou 3100 acidentes com vítimas (com algum tipo

de lesão) e 1645 acidentes sem vítimas (apenas com danos materiais) entre 2014 e 2017. Fernandes [18] complementa ao informar que, para o período analisado, foram registrados 941 Autorizações de Internação Hospitalar (AIH) referentes a fraturas identificadas como oriundas de acidentes de trânsito, conforme consta no DATASUS. Entretanto, deste total apenas 692 foram de fato acessadas para a realização de sua pesquisa. Ainda segundo Fernandes [18], as internações custaram ao município R$ 280,7 mil no ano de 2014, R$ 599,7 mil no ano de 2015, R$ 269,5 mil em 2016 e apenas R$ 22,3 mil em 2017. Diante deste cenário, conclui-se que o trânsito local traz um quadro preocupante não apenas pelas cifras financeiras, mas também pela falta de metodologias eficazes em seu monitoramento e controle.

3 Método

As etapas para a realização desta pesquisa são apresentadas na Figura 1.

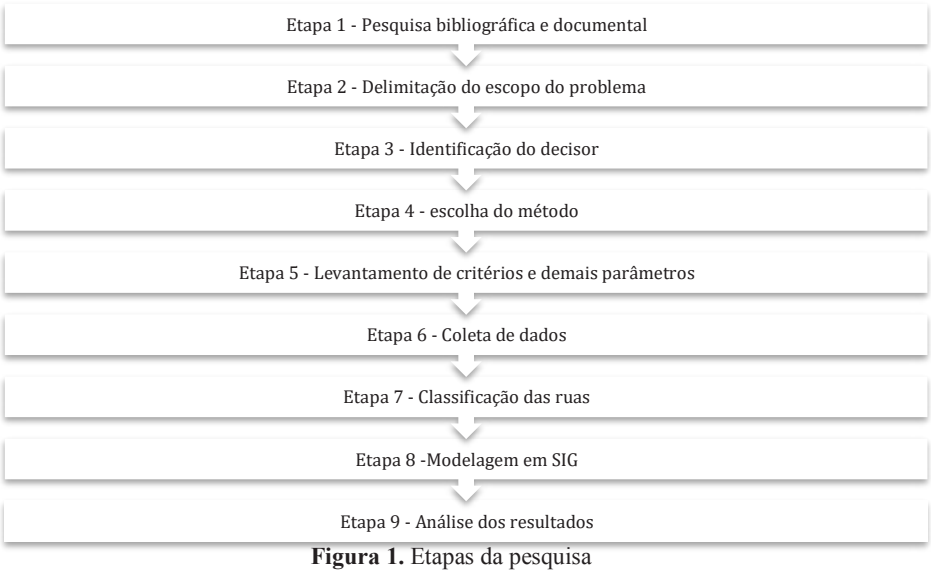

Figura 1. Etapas da pesquisa

Inicialmente, foi realizada pesquisa bibliográfica acerca dos temas relacionados ao objetivo da pesquisa. Em seguida, foi realizada uma pesquisa documental, de modo a se coletar dados relacionados a acidentes de trânsito no Mundo, no Brasil e no estado do Rio Grande do Norte. Na Etapa 2, o escopo da pesquisa foi delimitado. Desta forma, definiu-se realizar o estudo no Município de Mossoró-RN, cidade onde está localizada a Universidade. Na Etapa 3, foi identificado o tomador de decisão, cujas preferências serão consideradas no processo. O decisor escolhido foi um especialista na área, Doutor em Engenharia dos Transportes e coordenador de um projeto de pesquisa desenvolvido pela Universidade Federal Rural do Semi Árido e Universidade do Estado do Rio Grande do Norte e os órgãos de trânsito da cidade alvo. A partir de conversas com o

mesmo, definiu-se adotar a problemática de classificação, ou seja, alocar as ruas em classes, conforme sua criticidade.

A seguir, na Etapa 4, o método multicritério foi escolhido, de acordo com a estrutura de preferências do tomador de decisão. Neste ponto, foi escolhido o método PROMSORT (PROMETHEE Sorting). Considerando os pontos propostos por Roy e Slowinski [19], o método foi escolhido por fornecer solução para problemática de classificação, por considerar um grupo finito de alternativas (não há inclusão de novas alternativas após a análise dos dados), por considerar escalas verbais e numéricas, pelo caráter não compensatório (não possibilitando compensação direta de desempenhos entre critérios) e por possibilitar a consideração da hesitação dos decisores (através de funções de preferências e limiares).

Na Etapa 5, com base no método escolhido, foram levantados os critérios que o decisor considera importantes para se avaliar a criticidade em uma via, bem como parâmetros. Em seguida, na Etapa 6, foi realizada a coleta dos dados relacionados às vias. Parte dos dados foi coletada diretamente junto ao tomador de decisão, explicitando as suas preferências. Dados técnicos e de número de acidentes sem vítimas foram levantados junto a Secretaria de Mobilidade Urbana (SEMOB) do Município de Mossoró/RN. A coleta dos acidentes com vítimas, foi realizada através de uma parceria com o 2° Distrito de Polícia Rodoviária Estadual, responsável pelo município. Foram coletados dados referentes aos registros emitidos pelas instituições para cada acidente, entre os anos de 2015 e 2017, incluindo as coordenadas onde ocorreu cada acidente.

Na Etapa 7, por sua vez, o método PROMSORT foi aplicado e as vias foram classificadas em uma das três classes previamente definidas, com analogia a um semáforo: (1) Classe vermelha: as vias mais críticas, que requerem atenção imediata dos gestores; (2) Classe amarela: as vias com criticidade média, que requerem atenção assim que possível; (3) Classe verde: as vias em condição mais satisfatória e que não requerem atenção imediata. Salienta-se que, nessa etapa, 19 ruas foram excluídas, pois não apresentavam dados referentes aos critérios escolhidos. Na Etapa 8 foi elaborada a representação geográfica dos resultados obtidos, com o objetivo de se facilitar a análise dos resultados por parte dos gestores. Por fim, na Etapa 9, os resultados foram discutidos.

Para a execução do trabalho, o método PROMSORT foi escolhido, sendo ele baseado nos métodos da família PROMETHEE, utilizando o PROMETHEE I em sua primeira etapa. Desenvolvido por Araz e Ozkarahan [20], o método atribui as alternativas a categorias ordenadas predefinidas. Como destacado por Oliveira [21], para se designar uma determinada alternativa a uma das categorias, compara-se essa alternativa com valores pré-estabelecidos que servem como fronteiras de classe e também com alternativas de referência.

Segundo Araz e Ozkarahan [20], a implementação do PROMSORT se dá em três etapas definidas:

- Uso do PROMETHEE I para a elaboração das relações de sobreclassificação, encontrando nesta etapa os fluxos positivos (que representam a preferência de uma alternativa sobre as demais) e negativos (o grau de preferência de todas as outras);
- Usando as relações encontradas no passo anterior para designar as alternativas a cada categoria previamente estabelecida;

- Diante de casos de indiferença e incomparabilidade, proceder com a atribuição usando comparação por pares.

Segundo Brans, et al. [22] os métodos da família PROMETHEE destacam-se ao envolver conceitos e parâmetros que possuem alguma interpretação física ou econômica, de fácil entendimento para o tomador de decisão. Brans e Vincke [23] apontam que, designados pesos p_j, representando grau de importância para cada critério, o grau de sobreclassificação π(a,b) é computado de acordo com a equação abaixo:

$$\pi(a,b) = \frac{1}{P}\sum_{j=1}^{n} \quad p_j F_j(a,b), \quad onde\ P = \sum_{j=1}^{n} \quad p_j \qquad (1)$$

Onde $F_j(a,b)$ é um número entre 0 e 1 que aumenta quando $g_j(a) - g_j(b)$ aumenta e é igual a zero se $g_j(a) \leq g_j(b)$. Para que se encontre o valor da função $F_j(a,b)$, o tomador de decisão pode escolher, para cada critério, uma das seis formas de curvas, representadas por limiares de indiferença (q) e de preferência (p): (1) Critério usual, quando não há parâmetro a ser definido; (2) Quase-critério, para a qual define-se o parâmetro q; (3) Limite de preferência, definindo o parâmetro p; (4) Pseudo-critério, considerando os parâmetros q e p; (5) Área de indiferença, considerando, também, os parâmetros q e p; (6) Critério Gaussiano, no qual o desvio padrão deve ser fixado.

Assim, de acordo com a maneira como a preferência do tomador de decisão aumenta, com o aumento do $g_j(a) \leq g_j(b)$, o tomador de decisão escolhe, para cada critério, a forma da função e os seus parâmetros associados. Estes, por sua vez, têm simples interpretação, representando limiares de indiferença e preferência.

Uma vez obtidos os valores de $\pi(a,b)$, duas pré-ordens completas podem ser obtidas, sendo a primeira representando uma ordenação de ações seguindo ordem decrescente dos números $\varphi^+(a)$:

$$\varphi^+(a) = \frac{1}{n-1}\sum_{b\in A} \quad \pi(a,b) \quad (Fluxo\ de\ saída) \qquad (2)$$

E outro seguindo a ordem crescente dos números $\varphi^-(a)$:

$$\varphi^-(a) = \frac{1}{n-1}\sum_{b\in A} \quad \pi(b,a) \quad (Fluxo\ de\ entrada) \qquad (3)$$

A intersecção destes dois fluxos gera a pré-ordem parcial resultado da aplicação do método PROMETHEE I.

Na próxima etapa de aplicação do PROMSORT, as categorias são definidas por limites superiores e inferiores, onde as alternativas são comparadas com os perfis limite, utilizando as relações de sobreclassificação encontradas com a aplicação do PROMETHEE I. Desta forma, a comparação de uma alternativa com o perfil limite estabelece em qual classe cada alternativa será inserida, a partir das relações obtidas com as equações abaixo [20].

$$(aPb_h)\ se \begin{cases} \phi^+(a) > \phi^+(b_h)\ e\ \phi^-(a) < \phi^-(b_h)\ ou \\ \phi^+(a) = \phi^+(b_h)\ e\ \phi^-(a) < \phi^-(b_h)\ ou \\ \phi^+(a) > \phi^+(b_h)\ e\ \phi^-(a) = \phi^-(b_h) \end{cases} \qquad (4)$$

a é indiferente em relação à b_h:

$$(aIb_h)\ se\ \phi^+(a) = \phi^+(b_h)\ e\ \phi^-(a) = \phi^-(b_h) \tag{5}$$

a é incomparável a b_h:

$$(aRb_h)\ se \begin{cases} \phi^+(a) > \phi^+(b_h)\ e\ \phi^-(a) > \phi^-(b_h)\ ou \\ \phi^+(a) < \phi^+(b_h)\ e\ \phi^-(a) <\ \phi^-(b_h) \end{cases} \tag{6}$$

De acordo com Araz e Ozkarahan [20], atribuição das alternativas nas categorias escolhidas é possível com o uso dessas relações. Entretanto, é possível que alternativas possam acabar não sendo incluídas em alguma das alternativas, por incomparabilidade ou indiferença. Na etapa seguinte, o método utiliza as alternativas alocadas às categorias como referência para as que não foram incluídas.

Estabelece-se a diferença do ponto de corte d_k: tal ponto s compreende valores entre 0 e 1, usando um ponto de vista otimista ou pessimista, a critério do decisor. Se s for 0, as alternativas não classificadas serão alocadas de acordo com suas funções distância. Com s = 1, elas serão atribuídas às classes mais baixas.

$$d_k = \frac{1}{n_t} d_k^+ - \frac{1}{n_{t+1}} d_k^- \tag{7}$$

Onde:

d_k^+ : sobreclassificação de a sobre todas as alternativas alocadas a uma categoria C_t, e:

$$d_k^+ = \sum_{xeXt} \left(\Phi(a) - \Phi(x)\right) \tag{8}$$

d_k^- : sobreclassificação de a sobre todas as alternativas alocadas a uma categoria C_{t+1}, e:

$$d_k^- = \sum_{xeXt} \left(\Phi(x) - \Phi(a)\right) \tag{9}$$

n_t sendo o número de alternativas de referência da categoria C_t.

Aplicação do ponto de corte s: sendo a diferença maior que o ponto de corte s, classificar a alternativa a à categoria C_{t+1}, senão à C_t.

A seguir é apresentada a aplicação numérica para o caso da cidade de Mossoró, RN.

4 Aplicação numérica

A aplicação foi realizada considerando-se todas as ruas da cidade, desconsiderando-se as 19 excluídas, conforme apresentado na seção 3. Uma vez definidos o método e o decisor, foram levantados os critérios que tornam uma via mais crítica, sob o ponto de vista do decisor, conforme apresentado na Tabela 1.

Tabela 1. Critérios considerados pelo tomador de decisão.

Cod	Critérios	Descrição	Max/Min	Escala
C1	Sinalização vertical	Placas existentes nas vias.	Min	Likert (5 pontos)
C2	Sinalização horizontal	A sinalização pintada nas vias.	Min	Likert (5 pontos)
C3	Sinalização semafórica	Presença de sinais de trânsito nas vias.	Max	Sim/Não
C4	Velocidade	A velocidade da via. (30, 40 ou 50 km/h).	Max	Numérica
C5	Largura	A largura da via, que varia com o tipo.	Max	Numérica
C6	Acidentes sem vítimas	Nº. de ocorrências apenas com danos materiais.	Max	Numérica
C7	Acidentes com vítimas	Ocorrências com lesão corporal ou óbito.	Max	Numérica
C8	Conservação da via	Indica o estado de conservação em que se encontra a via.	Min	Likert (5 pontos)

Para a maioria dos critérios adotou-se a escala quantitativa. No entanto, para os critérios de sinalização vertical e horizontal, presença de semáforos e conservação da via foi utilizada uma escala qualitativa, que é uma escala verbal traduzida em uma escala ordinal. No que se refere ao critério Largura, tem-se diversos tipos de vias: Arterial I (20 m), Arterial II (18 m), Coletora I (15 m), Coletora II (14 m) e Arruamentos (12 m). Neste critério, segundo o decisor, quanto mais larga a rua, mais crítica pois os condutores tendem a acelerar mais.

Em seguida, o decisor estabeleceu os pesos para cada um dos critérios, representando a importância que ele atribui a cada um deles na criticidade de uma via. O decisor foi informado que ele poderia atribuir os valores livremente mas, tendo em mente que o valor 2x definido para um critério implica que ele possui duas vezes mais importância do que um critério que recebeu peso x. Os pesos definidos pelo decisor são apresentados

na Tabela 2. Quanto às funções de preferência do método PROMETHEE, foi definido utilizar a função usual para todos os critérios. Desta forma, qualquer diferença no desempenho das alternativas implica em sobreclassificação, para aquele critério. O método PROMETHEE foi, então, aplicado, obtendo-se os fluxos de entrada e de saída para cada uma das vias.

Posteriormente, foram definidos limites dos perfis b_1 e b_2, que delimitam as classes. Esses limites podem ser considerados alternativas fictícias, cujo objetivo é determinar as fronteiras das classes, sendo as alternativas de pior desempenho em relação ao perfil b_1 pertencente à classe verde, as alternativas avaliadas entre b_1 e b_2 pertencentes à classe amarela e as avaliadas como melhores que b_2 pertencentes à classe vermelha.

Para encontrar os limites de classe para o quantitativo de acidentes, o decisor analisou quais os limites que caracterizariam a classificação de uma via, para cada critério. Para os critérios de número de acidentes, este propôs a aplicação do Princípio de Pareto. A partir da base de dados, o quantitativo de acidentes que compõem os 10% das vias com mais acidentes faz a fronteira da classe vermelha com a amarela. Os 20% seguintes, separam a classe amarela da verde. Desta forma, 70% das vias com menos acidentes seriam alocadas na classe verde, para este critério.

Tabela 2. Pesos e perfis limites para aplicação do PROMSORT.

Critérios	C1	C2	C3	C4	C5	C6	C7	C8
Peso	0,0740	0,0925	0,0740	0,1851	0,1296	0,1481	0,1851	0,1111
b_1	1	1	0	30	14	2	2	2
b_2	3	4	1	50	18	39	54	4

O método PROMSORT foi aplicado. Inicialmente, 22 ruas foram alocadas na classe vermelha e 6 ruas ficaram na classe amarela. 2179 vias foram classificadas na classe verde, sendo ruas de baixa criticidade. Entretanto, 60 ruas não foram classificadas nessa primeira etapa, pois foram "Incomparáveis com b_1", o primeiro limite de classe que separa as classes verde e amarela. Esse montante representa 2,64% do total de ruas.

Foi necessário, então, definir um ponto de corte com o decisor para a próxima fase de avaliação do PROMSORT, sendo este definido como 0. Tal ponto servirá para alocar as alternativas não alocadas na primeira fase. Foi encontrado então um d_k^+, que representa a sobreclassificação da alternativa em relação a uma categoria C_t, neste caso a categoria mais baixa (Verde) e um d_k^-, por sua vez representando a sobreclassificação da alternativa perante uma categoria C_{t+1}, superior, neste caso a Amarela.

Se o resultado líquido d_k for superior ao ponto de corte, neste caso $d_k > 0$, a alternativa seria alocada à Classe Amarela. Por sua vez, se for menor que o ponto de corte, aloca-se à Classe Verde. A partir desta operação, acabou-se por classificar essas ruas na Classe Verde. Desta forma, na Figura 2 são apresentados o resultado da classificação.

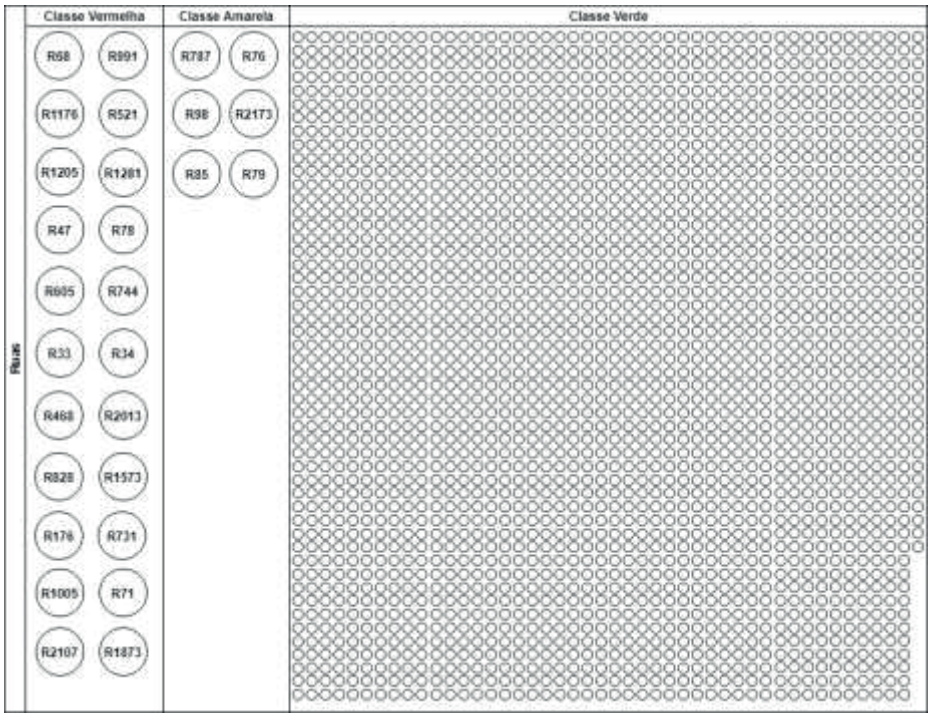

Figura 2. Representação das vias após a classificação

Conforme pode-se observar na Figura 2, a maior parte das vias ficou posicionada na classe verde, em análise comparativa com as demais vias do município. As Tabelas 3 e 4 apresentam as vias que foram classificadas nas classes vermelha e amarela.

Tabela 3. Vias alocadas na classe vermelha

Código da via	Nome
R68	Avenida Presidente Dutra
R991	Rua Francisco Solon
R1873	Rua Prudente De Morais
R1176	Rua Jeremias Da Rocha
R521	Rua Coronel Vicente Saboia
R2107	Rua Tarcísio Correia
R1205	Rua João Falcão

R1281	Rua José Damião
R71	Avenida Rio Branco
R47	Avenida Joao da Escossia
R78	Avenida Sérvulo Marcelino
R1005	Rua Frei Miguelinho
R605	Rua Delfim Moreira
R744	Rua Duodecimo Rosado
R731	Rua Doutor João Marcelino
R33	Avenida Diocesana
R34	Avenida Dix - Neuf Rosado
R176	Rua Alfredo Fernandes
R468	Rua Coelho Neto
R2013	Rua Santos Dumont
R1573	Rua Marechal Deodoro
R828	Rua Felipe Camarão

As vias apresentadas na Tabela 3 carecem de maior atenção por parte dos gestores públicos. Dessas vias, 8 são classificadas como Arteriais II, como as Avenidas Diocesanas, Dix Neuf Rosado, João da Escóssia e Presidente Dutra, algumas das vias mais movimentadas da cidade. Outras 8 são Coletoras I e 3 são Coletoras II. Com exceção de uma que é pavimentada de paralelepípedo, todas as outras são asfaltadas, sendo 9 com um pavimento com estado de conservação regular, 3 em bom estado e 7 ruins. A maior parte destas se concentram na região central da cidade. Destoa dessa distribuição a parte inicial da rua João Falcão, via de entrada de um bairro bastante populoso da cidade e a rua Tarcísio Correia, que liga o outros dois bairros. Essas ruas se destacam ainda por ter uma péssima sinalização horizontal (16 foram avaliadas com 1) e vertical (13 tiveram avaliação 1), além de serem quase todas de alta velocidade (11 tem velocidade de 50 km/h) e somarem 1357 acidentes com vítimas e 750 sem vítimas.

Tabela 4. Vias alocadas na classe amarela

Código da via	Nome

R787	Rua Epitácio Pessoa
R76	Avenida São Jerônimo
R79	Avenida Walter Wanderley
R2173	Rua Vicente Fernandes
R98	RN - 117
R85	Br - 304 - Avenida Industrial Dehuel Vieira

As vias alocadas na classe Amarela 2 são do tipo Arterial I, as Br - 304 em seu trecho de saída para Fortaleza e a RN - 117 na divisa entre os bairros Itapetinga e Bom Jesus, 1 é do tipo Arterial II (Rua Epitácio Pessoa, ligando o Bom Jardim as Barrocas) e as demais são Coletoras II, geralmente ruas importantes dentro dos bairros, captando o fluxo das Arteriais. Todas obtiveram a menor avaliação nos critérios C1, C2 e C8 (sinalização vertical, horizontal e estado de conservação respectivamente). Também possuem velocidades medianas para alta, metade com 50 km/h e metade com 40 km/h.

Foi realizada análise de sensibilidade, analisando especialmente as ruas classificadas como Vermelha e Amarela. Aumentou-se, em 20%, o valor dos pesos atribuídos a cada critério, reduzindo proporcionalmente os demais, de modo a se analisar se haveria alterações nas vias alocadas nas respectivas classes. Em linhas gerais, a variação entre as posições nos critérios foi mínima. As ruas R68, R991, R1873 e R1176 permaneceram em suas posições em todos os critérios para a classe vermelha. Apenas quando se aumentou o peso dos acidentes sem vítimas (C6), obteve-se mais ruas que os demais, totalizando 32 ruas nesta classificação, sendo 7 ruas únicas, ou seja, que não apareceram em nenhum outro critério quando foram analisados.

As posições para a classe amarela também variaram pouco. A mudança do critério de acidentes sem vítimas (C6), ocasionou redução na quantidade de ruas na classe amarela, com 4 delas indo para a classe vermelha (Epitácio Pessoa, Avenida São Jerônimo, Avenida Walter Wanderley e rua Vicente Fernandes). Quando se aumentou o peso para velocidade (C4), observou-se mais ruas sendo classificadas como classe amarela, passando para 9, sendo 3 ruas únicas, sem presença em outros critérios. Tais ruas na análise original estavam na classe verde.

Por fim, os resultados obtidos foram associados a base geoespacial original, de modo a criar um mapa temático, apresentado na Figura 3. Tais mapas permitem que o gestor facilmente assimile informações cruciais, de modo a adotar rapidamente as ações necessárias.

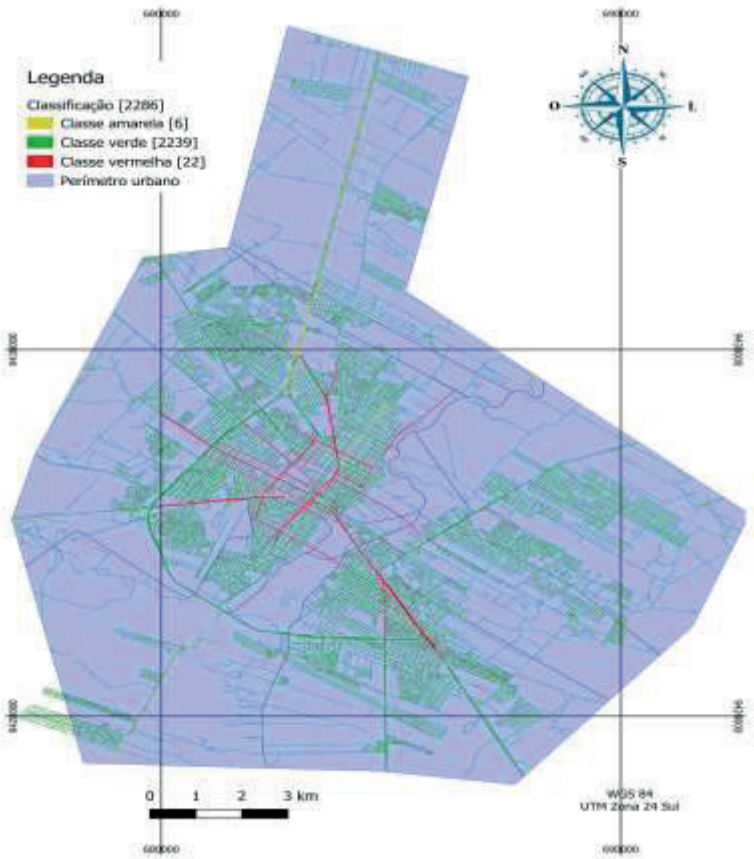

Figura 3. Mapa das vias da cidade após a classificação

A partir da análise da Figura 3, podemos ver que algumas das principais vias da cidade, como (R34) Avenida Dix Neuf Rosado, (R71) Avenida Rio Branco e (R68) Avenida Presidente Dutra, que conectam os extremos do município e tem um maior fluxo de veículos, foram classificadas como vermelha, demandando intervenção imediata. Além disso, dentro do SIG, é possível aplicar zoom no mapa e identificar visualmente quais vias estão alocadas em cada uma das classes. Isso pode ajudar o gestor a visualizar a relação entre as vias e entender como se relacionam os fatores de risco para as vias. Além disso, a representação geográfica dos resultados pode ser importante para facilitar a comunicação entre todos os envolvidos na gestão de trânsito e prover possibilidade de acompanhamento das condições das vias periodicamente.

5 Considerações finais

Os acidentes de trânsito tornaram-se uma verdadeira epidemia no Brasil, gerando prejuízos sociais, econômicos e humanos. Além disso, sobrecarregam os serviços públicos de saúde, o que prejudica o atendimento para todos. Neste sentido, melhorar o processo de tomada de decisão para priorização de onde o Poder Público deve agir, pode gerar bons resultados e maximizar os ganhos sociais com as intervenções realizadas. Diante deste contexto, é proposto um modelo multicritério para apoiar o processo de tomada de decisão, classificando as ruas em uma das três classes críticas: vermelha, amarela e verde. Para tanto, é proposta a utilização do método PROMSORT, que permitiu que fossem analisadas diversas características quantitativas e qualitativas, em uma grande quantidade de alternativas (após os processamentos, chegou-se a 2267 ruas únicas). Em seguida, os dados obtidos foram representados geograficamente e pôde-se constatar quais as áreas mais críticas para atuação dos gestores públicos.

Destacam-se algumas limitações do estudo. Em termos práticos, devido a elevada rotatividade nas pessoas que tomam decisões quanto ao trânsito, os parâmetros definidos pelo tomador de decisão podem ser alterados com certa frequência. Além disso, a própria utilização do modelo depende de um esforço dos gestores que podem passar a atuar no setor, a cada eleição, entendam a importância do mesmo. Outra limitação envolveu a consideração de apenas um tomador de decisão. Neste sentido, propõe-se, como sugestão de trabalhos futuros, a adequação do modelo para um contexto de múltiplos tomadores de decisão.

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Análise das dimensões da inovação pela ótica das camadas de gestão e operacionais

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Resumo. Nos últimos anos o termo inovação encontra-se em evidência. A mudança dos ambientes corporativos e a necessidade de inserção de novas tecnologias que ficam obsolescentes cada vez mais rápidas, fazem com que decisões sobre qual destas utilizar seja bem fundamentada e baseie-se em critérios de relevância pelos diversos membros do setor. O impacto de uma decisão pode gerar uma linha tênue entre ganhos e prejuízos grandes para a empresa. A melhor maneira de contornar os impactos é tomar a decisão levando-se em consideração as principais dimensões da inovação. O artigo traz uma pesquisa sobre a preferência das camadas operacionais e de gestão de uma empresa de grande porte com relação às dimensões da inovação. A pesquisa foi realizada fazendo uso do método AHP (*Analytic Hierarchy Process*) comparando as dimensões. A ferramenta com AHP foi desenvolvida em python, sendo voltada à web, o que tornou possível a sua realização de uma forma mais rápida e de maneira remota.

Keywords: AHP, Dimensões da inovação, Tomada de decisão.

1 Introdução

A inovação, como peça determinante para o sucesso e prosperidade das organizações e países vem sendo estudada há vários anos, porém, no atual contexto de instabilidade econômica e política mundial, globalização da economia, avanços tecnológicos competição por recursos e consumidores, a inovação está tornando-se preponderante para a própria sobrevivência das organizações.

Tanto o meio acadêmico como o meio empresarial têm visto na capacidade de gerar soluções inovadoras uma fonte de diferencial estratégico para obter-se vantagem competitiva.

No entanto, desafios e pressões são apresentados às empresas para que a inovação aconteça de forma sustentável e contínua. Tempo e recursos devem ser disponibilizados para que as organizações possam vencê-los e gerar um ambiente apropriado à atividade inovadora nos diversos níveis da organização.

Diversos obstáculos se apresentam à inovação. Estes obstáculos podem ser de origem econômica, tais como, alto custo da inovação e dificuldades de financiamento. Podem também estar no campo do risco ao investimento, uma vez que inovação de-

pende da aceitação do público consumidor e até nas dificuldades de pessoal especializado e motivação para inovar. Soma-se a isto as incertezas tecnológicas, mercado e as próprias barreiras culturais e de gestão das empresas.

Desta feita, onde há obstáculos se buscam modos de suprimi-los. Diversos estudos identificam fatores ou dimensões, que se observados e mensurados, podem conduzir a organização a um caminho mais suave rumo a atividade inovativa.

Ainda assim, mesmo que o conhecimento sobre estes fatores fosse de conhecimento da camada de gestão das organizações, o conhecimento deveria ser difundido e aceito pelas camadas operacionais, geralmente quem produz a inovação. Entretanto, a comunicação entre estes níveis empresariais nem sempre é tido como satisfatório, podendo ensejar uma sequência de dificuldades.

O presente estudo pretende explanar as principais características da inovação, sua conceituação, seus obstáculos e dimensões para que a inovação aconteça. O principal propósito é observar através de método multicritério se a compreensão das dimensões e sua ordem de importância é uniforme entre as diferentes hierarquias de membros da camada gestora e depois entre esta e a camada operacional.

1.1 Referencial Teórico

1.1.1 Inovação

Muito tem se falado da necessidade da inovação para gerar diferencial estratégico para as organizações, promovendo a melhora de performance, desempenho e consequente lucratividade.

Schumpeter, em sua obra Theory of economic development (1911), já demonstrava a relação entre empreendedorismo e a inovação, reforçando a importância desta relação para as organizações. Ele cunhou o termo “destruição criativa” para demonstrar que empreendedores obsoletavam recursos e infraestrutura existentes, causando sua renovação. Este conjunto de atos, habilidades e ousadia das pessoas ensejaram o surgimento de novos produtos, processos e serviços nas organizações. Assim, as organizações surgiam, eram mantidas e cresciam de forma lucrativa (THIMÓTEO, 2020).

Assim, o capitalismo, motor da competição econômica, não poderá se manter em estado estacionário. É a inovação que “incessantemente revoluciona a estrutura econômica a partir de dentro, incessantemente destruindo a velha, incessantemente criando uma nova” (SCHUMPETER, traduzido em 2017).

Ao longo do tempo, tornou-se claro que a inovação gerando progresso tecnológico promove o incremento da produtividade, a geração de novos produtos e serviços, aumentando o desempenho e muitas vezes sendo fator decisivo para o sucesso das organizações (MOTOHASHI, 1998).

Estudos de NELSON (1992) e ROSENBERG (1982) já apontavam sobre o papel importante da inovação tecnológica para o aumento da competitividade global, na medida em que melhoravam o desempenho das organizações.

Da forma oposta, a inércia com relação ao comportamento inovador ocasiona o aprisionamento do potencial das organizações, mantendo-as cada vez mais distante das organizações que tem inovação no seu referencial estratégico e que realmente a promove. Como demonstração disto, o estudo de LEDERMAN et al (2014) informa

que o baixo índice de soluções inovadoras tem levado as organizações latino-americanas a um crescimento mais lento comparado a outras regiões.

SHUMPETER (2017) ensina que em um mundo estacionário, sem inovação e desenvolvimento econômico, a competição poderia reduzir os lucros para um nível "normal". Mas, dentro de um desenvolvimento dinâmico, lucros acima do normal são frequentemente a recompensa das organizações inovadoras.

O tema da inovação, portanto foi discutido por diversos autores e sua conceituação vem sendo desenvolvida ao longo do tempo.

SCHUMPETER (2017) já conceitua a inovação como uma ação ou conjunto de ações que é aplicado industrialmente ou mesmo no comércio na forma de produtos, formas de produção, processos, suprimentos ou outros insumos. Estas ações trazem no seu núcleo uma nova organização de negócios ou das relações de trabalho.

A Organização para Cooperação e Desenvolvimento Econômico (OCDE) também define inovação no Manual de Oslo. Para a OCDE (2006), inovação se define como "a implementação de um produto, bem ou serviço novo ou significativamente melhorado, ou ainda um processo ou um novo método de marketing ou um novo método organizacional nas práticas de negócio na organização do local de trabalho ou nas relações externas".

Já a Lei de Inovação (2004) define inovação como "introdução de novidade ou aperfeiçoamento no ambiente produtivo e social que resulte em novos produtos, serviços ou processos ou que compreenda a agregação de novas funcionalidades ou características a produto, serviço ou processo já existente que possa resultar em melhorias e em efetivo ganho de qualidade ou desempenho".

MOYSÉS & LIPPI (2003) adverte que não se deve considerar como inovação qualquer invenção advinda da mente humana. Para ele, invenção significa uma criação intelectual de algo inexistente e que pode não ter consequências econômicas, enquanto inovação consiste em uma ideia efetivamente incorporada aos sistemas produtivos levando a resultados econômicos. Tal ideia é corroborada por QUANDT (2009) que afirma ser uma invenção a concepção de algo inédito independentemente de sua aplicação comercial ou mesmo utilidade prática, enquanto inovação está atrelada à transformação de conhecimento em valor, pela introdução de novos produtos processos ou sistemas no mercado, ou seja, a inovação deve ser revestida de potencial econômico.

No mesmo bojo de ideias, a Lei do Bem (2006) definiu inovação como "a concepção de novo produto ou processo de fabricação, bem como a agregação de novas funcionalidades ou características ao produto ou processo que implique em melhorias incrementais e efetivo ganho de qualidade ou produtividade, resultando maior competitividade no mercado".

1.1.2 Obstáculos à inovação no Brasil

Se a inovação, gerada pela força do capital humano tem sido um propulsor do progresso e desenvolvimento econômico de empresas e países (DIEBOLT & HIPPE, 2019), por outro lado, esta mesma inovação encontra obstáculos à sua geração.

O manual de OSLO (2005) aponta os principais fatores dificultadores da Inovação, separando-os em 3 grupos, sendo eles: Fatores econômicos, fatores da empresa e outras razões diversas.

A tabela 1 desdobra os grupos em fatores individualizados.

Tabela 1. Obstáculos à atividade de inovação. (Adaptado OCDE, 2005)

Grupo	Itens
Fatores econômicos	Riscos excessivos percebidos
	Custo muito alto
	Falta de apropriadas de financiamento
	Prazo longo de retorno de investimento
	Potencial de inovação insuficiente
	Falta de pessoal qualificado
	Falta de informações sobre tecnologia
Fatores da empresa	Falta de informações sobre os mercados
	Dificuldade em controlar gastos com inovação
	Resistência interna às mudanças
	Deficiências na disponibilidade de serviços externos
	Falta de oportunidades para a cooperação
	Falta de oportunidade tecnológica
Outras razões	Falta de infraestrutura
	Nenhuma necessidade de inovar devido a inovações anteriores
	Fraca proteção aos direitos de propriedade
	Legislação, normas, regulamentos e padrões impostos
	Clientes indiferentes a novos produtos e processos

Os fatores apontados pelo Manual de Oslo aparecem em diversas pesquisas feitas no Brasil tanto por pesquisadores da academia, quanto por relatórios governamentais.

No Brasil, empresas pesquisadas pelo IPEA para a consolidação da nota técnica IPEA (2009) apontaram como seus principais obstáculos à inovação fatores associados ao crédito, sendo eles: Riscos econômicos excessivos, elevados custos da inovação e escassez de fontes apropriadas de financiamento.

Quandt (2009), na mesma esteira, além dos itens acima, cita: escassez de recursos próprios, falta de pessoal qualificado, resposta fraca de consumidores a novos produtos e falta de informação sobre tecnologias e mercados.

QUANDT et al (2013) estuda fatores associados à inovação dividindo-os em dimensões que podem ser relacionadas ao sucesso ou fracasso nas iniciativas de inovação. As dimensões são: Estratégia e objetivos, Liderança, Cultura e valores, Estrutura organizacional, Processos, Gestão de recursos humanos e competências, Relacionamento externo, Infraestrutura tecnológica e sistemas de informação, Medição de resultados e recompensas e Aprendizagem.

MAIA & SILVA (2016) lembram que a capacidade inovadora varia entre as empresas e pode ser determinada por um grande e complexo número de fatores. Estes fatores tanto impulsionam quanto limitam o processo de inovação empresarial.

Muitas variáveis afetam o resultado esperado referente ao processo de inovação. Estas variáveis podem ser de caráter econômico, cultural, corporativista e legal, portanto essas barreiras devem ser consideradas no momento do planejamento da gestão da inovação no âmbito empresarial (MELLO et al., 2013)

1.1.3 Dimensões da inovação

Diversos autores estudaram ferramentas para promover a inovação, seja nos aspectos da gestão da inovação ou mesmo na capacidade de inovar. Várias ferramentas e modelos conceituais foram apresentados ao longo do tempo. Neste trabalho, foram analisadas ferramentas que propõem a análise por dimensões, assim selecionamos as ferramentas a seguir:

1. (OI) Octógono da inovação proposto por Scherer & Carlomagno (2009);
2. (DI) Dimensões organizacionais da inovatividade proposto por Quandt, Ferraresi & Bezerra (2013);
3. (IIF) Integrated Innovation Framework, proposto por Nada, KHoleif, Elbadawy & Yanik (2010);

As abordagens citadas têm em comum o modelo baseado em dimensões que influenciam a inovação nas corporações, variando entre elas a quantidade e significados.

Apesar das ferramentas se basearem em dimensões de análise nota-se que entre estes autores:

1. Não há coincidência total de dimensões entre as ferramentas;
2. Nas dimensões que são coincidentes, seus significados são similares ou mesmo complementares;
3. As dimensões englobam questões típicas relacionadas à inovação, não observamos conflitos ou dimensões antagônicas.

1.1.4 Comunicação entre a alta gestão e camadas operacionais sobre inovação

As organizações, geralmente, procuram melhorar a comunicação entre a alta gestão e as camadas operacionais com o objetivo de melhorar a produtividade e se manterem no mercado.

Bueno (2007), aponta que os problemas de comunicação podem interferir negativamente na vida das organizações. Ele afirma que empregados mal informados ou descontentes podem gerar prejuízos pois expressam com mais autenticidade valores positivos ou negativos sobre a cultura organizacional, uma vez que, “afinal de contas, eles estão vivendo lá dentro”.

Por esta razão, a comunicação interna ganha destaque no sentido de promover mudanças, ajustar comportamentos e qualificar seus empregados. Ao fim, busca-se a melhoria de desempenho, produtividade e consequente lucratividade.

JACOMINI (2011) ensina que a produtividade dos empregados está diretamente ligada à qualidade da informação que recebem e consequente envolvimento com a missão. Por isto a comunicação tem papel preponderante na boa gestão operacional. A

comunicação adequada integra as pessoas e as motiva a compartilhar ideias e agregar valores à organização.

A mesma autora, no entanto, adverte que quando a comunicação não ocorre de forma correta e integrada, podem surgir transtornos que podem levar as iniciativas ao descrédito e mesmo ao fracasso. Comunicações má conduzidas e, portanto, mensagens recebidas com impedância podem gerar insegurança, desmotivação e falta de comprometimento dos empregados.

REGO (2010) adverte que, sendo uma organização de fato uma rede de comunicação, se a comunicação falha, uma parte da estrutura organizacional também falha.

O mesmo fenômeno pode ser observado nos processos de inovação. CARVALHO (2009) discute o processo de comunicação como condição essencial para que "a dinâmica interna produza e incorpore inovações". O mesmo autor ainda afirma que é a comunicação que permite que pessoas possam compartilhar conhecimento para mudar e inovar processos e produtos, sendo esta comunicação, objeto necessário para que "a cultura se renove e ocorra aprendizagem e criação".

Barañano (2005) entende a comunicação como essencial e medida básica para o sucesso dos processos de inovação. Ainda adverte que em organizações complexas, a comunicação encontra obstáculos, tornando-se um fator de suscetibilidade.

Com efeito, mesmo a comunicação das estratégias pode encontrar barreiras entre a gestão, responsável para estratégia das organizações e as unidades operacionais, responsável por levar a cabo tais estratégias. Mesmo processos estabelecidos podem encontrar barreiras devido ao isolamento das áreas multidisciplinares que atuam no mesmo processo. (GARCIA, 2011)

Desta forma, aquilo que é considerado importante para os gestores pode não ser considerado da mesma maneira pela camada operacional, criando disrupção no entendimento dos fatores essenciais, podendo levar iniciativas inovadoras ao fracasso.

2 Método Proposto

2.1 Classificação da pesquisa

Quanto à natureza, trata-se de uma pesquisa aplicada, pois busca gerar conhecimento para aplicação prática e direcionada a solução de problemas cotidianos.

A pesquisa tem características qualitativas, de caráter exploratório-descritivo, um estudo de caso, buscando compreender o comportamento e crenças de um grupo específico de pessoas, no entanto, por usar método multicritério, especificamente AHP, onde existem comparações par a par definindo um valor específico que define cada comparação, temos características quantitativas. Assim, quanto à abordagem, trata-se de uma pesquisa quali-quantitativa.

2.2 Procedimento da pesquisa

A pesquisa se deu nas áreas de tecnologia da informação (TI) de uma grande empresa situada no sul do Brasil (Empresa). Esta empresa conta com mais de 7000 em-

pregados sendo que destes, cerca de 150 trabalham diretamente com tecnologia da informação.

O "Nível operacional" está subordinado à cadeia de gestão da área em questão, que é composta por 3 níveis, sendo eles:

- "Nível gestor próximo";
- "Nível gestor intermediário";
- "Nível gestor superior";

O Nível gestor próximo se distingue por sua proximidade ao nível operacional, sendo diretamente responsável pelas funções operacionais da organização em questão.

O Nível gestor intermediário é responsável pelas ações táticas oriundas do planejamento estratégico. Tem o nível operacional e o nível gestor próximo como subordinados. Responde a Nível gestor superior.

O Nível gestor superior é responsável pelas definições estratégicas da área de tecnologia da informação. Subordina os demais níveis.

O modelo foi operacionalizado em 4 atividades distintas:

1 - A partir das descrições das dimensões da inovação foram levantadas 13 dimensões. Para cada dimensão levantou-se uma resenha baseada nas descrições.

2 - As dimensões e suas resenhas foram encaminhadas para 13 especialistas junto com uma planilha, onde estes especialistas deveriam marcar a ordem de importância, de acordo com seu entendimento, para cada uma das dimensões propostas. A classificação a ser apontada foi de 1 a 13, sendo 1 a mais importante e 13 a menos importante, não podendo haver repetição de valor.

Para cada dimensão, calculou-se a mediana das respostas dos especialistas, bem como seu desvio padrão. Isto se deu para a classificação das dimensões por ordem de importância na visão dos especialistas baseado na mediana. Caso houvesse empate, a dimensão que tivesse o menor desvio padrão teria a prevalência.

As 4 dimensões melhores classificadas foram selecionadas para a apreciação das pessoas da TI na empresa em ordem alfabética para não ocorrer qualquer tipo de influência nas respostas.

3 - As 4 dimensões foram apresentadas às pessoas da TI, posteriormente enquadradas nos níveis de gestão.

Estas receberam uma chave de acesso onde puderam classificar as 4 dimensões apontadas pelos especialistas utilizando o método AHP implementado no sistema. Os entrevistados classificaram as dimensões par a par informando o nível de relevância entre as dimensões. A relevância da dimensão "A" em relação à dimensão "B" foi classificada como:

- De igual importância;
- Um pouco mais importante;
- Muito mais importante;
- Extremamente mais importante;

O sistema disponibilizado para a pesquisa calculava de forma on-line o nível de inconsistência, solicitando ao entrevistado que corrigisse suas respostas caso esse nível fosse superior a 10%.

4 - As respostas de cada grupo foram unificadas pela mediana de seus resultados e estes resultados foram comparados.

Antes de apresentar a ferramenta aos respondentes, ela foi submetida à análise de 5 pessoas da organização para que validassem sua usabilidade. Esta fase foi útil para incrementar alguns controles e executar algumas correções.

3 Desenvolvimento

A tabela 2 mostra as escolhas dos especialistas após serem apresentadas 13 dimensões da inovação.

Tabela 2. Classificação das dimensões de acordo com os especialistas.

Ordem	Dimensão	Mediana	Desvio Padrão
1	Liderança	2	3,7296
2	Estratégia	3	3,1481
3	Pessoas	5	3,2621
4	Cultura e valores	5	3,5320
5	Infraestrutura, metodologias e ferramentas	6	3,0170
6	Estrutura organizacional	6	3,4044
7	Alocação de recursos	7	3,0234
8	Processos	7	3,3128
9	Aprendizagem	8	3,5210
10	Mensuração	9	2,7339
11	Relacionamento	9	2,8148
12	Funding	10	3,8180
13	Propriedade intelectual e comercialização	11	3,84

Conforme a aplicação da metodologia proposta, foram selecionadas as 4 dimensões mais bem classificadas.

Estas dimensões foram apresentadas aos respondentes através de e-mail, que continha a proposta do trabalho bem como uma descrição de cada uma das dimensões em ordem alfabética, além do acesso à ferramenta AHP desenvolvida para esta pesquisa. A descrição das dimensões apresentadas aos respondentes tinha o mesmo teor apresentado aos especialistas, porém com adaptação para a melhor compreensão de um público não acostumado com tema Inovação, conforme se vê na tabela 3.

Tabela 3. Descrição das dimensões apresentadas aos respondentes.

Dimensão	Descrição apresentada aos respondentes
Cultura e Valores	É a personalidade de organização. É composta pelas premissas, valores, normas e sinais tangíveis das lideranças da organização e seus comportamentos. A cultura e valores da empresa fortalecem o pensamento independente e a aplicação do conhecimento pessoal para os desafios organizacionais. Dá forte incentivo institucional ao questionamento e a quebra de paradigmas para gerar inovação. Está atrelado ao reconhecimento e recompensas.

Estratégia	O termo estratégia diz respeito à definição da "arena estratégica" para a inovação. Formulação de objetivos estratégicos de inovação, bem como o uso da inovação como instrumento estratégico para criar diferenciação. O entendimento que a inovação deve ter prioridade no planejamento estratégico da organização.
Liderança	O termo liderança no contexto deste estudo não se refere às pessoas que ocupam cargos de liderança, mas sim ao papel das lideranças para assegurar a eficácia do processo de gestão da inovação, inclusive considerando aspectos de comunicação, aprendizado e mudança, além da tolerância a riscos. Está atrelada ao grau de comprometimento que as lideranças e influenciadores tem para instituir ou propiciar a inovação.
Pessoas	O termo pessoas não se refere a um indivíduo ou mesmo ao conjunto dos indivíduos. O termo está atrelado a como a organização privilegia, estimula e recompensa seus empregados na busca da inovação. Como a organização se foca em indivíduos competentes, estimulados e dispostos ao enfrentamento dos desafios. Estas ações buscam garantir que todos os empregados conheçam os conceitos e a necessidade de inovar.

Neste mesmo e-mail, os respondentes receberam explicações básicas sobre o AHP, em especial sobre as comparações par-a-par e a necessidade de se obter um nível de inconsistência inferior a 10%.

Estas observações foram necessárias porque a ferramenta impedia que o respondente pudesse submeter suas respostas caso a inconsistência fosse superior a 10%, conforme preconizado pelo AHP.

A solução foi desenvolvida para ser executada tanto em computadores como para dispositivos móveis, fazendo uso de uma aplicação web utilizando o framework Django, escrito em python, que faz uso de linguagens javascript, CSS e HTML em modo responsivo para a interação com o usuário.

A figura 1 mostra a interface inicial que permite ao respondente comparar as dimensões propostas. O usuário faz a sua escolha deslizando o indicador em direção à sua preferência, formando assim a sua resposta.



Fig. 1. Interface da ferramenta.

Foram obtidas 51 respostas de um conjunto de 150 empregados da TI distribuídos da seguinte forma:

1. Gestor nível Superior: Posição máxima na TI, portanto 1 respondente;
2. Gestor nível intermediário: 3 respondentes;
3. Gestor nível próximo: 8 respondentes;
4. Nível operacional: 39 respondentes;

4 Resultados Observados

Após compilar os dados, encontramos os seguintes resultados seguindo os agrupamentos propostos pelo trabalho, a saber, nível operacional, nível gestor próximo, nível gestor intermediário, nível gestor superior.

As dimensões foram pontuadas e seus resultados compilados conforme a tabela 4 e apresentados no gráfico na figura 2:

Table 4. Resultados obtidos por nível.

Nível	Cultura e valores	Pessoas	Liderança	Estratégia
Operacional	0,25	0,35	0,02	0,12
Gestor Próximo	0,285	0,335	0,15	0,205
Gestor Intermediário	0,32	0,2	0,31	0,23
Gestor Superior	0,19	0,18	0,57	0,06

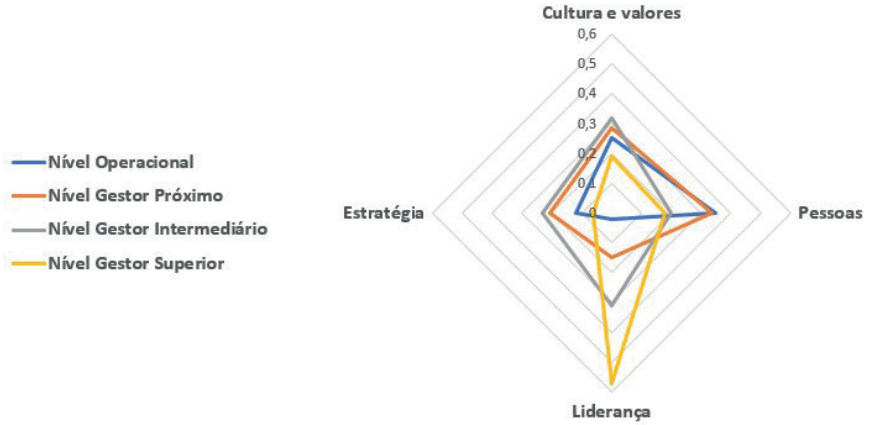

Fig. 2. Comparação das escolhas sobre as dimensões dos diferentes níveis

5 Considerações Finais

Ao observar o desenvolvimento do trabalho vê-se que a decisão por utilizar o AHP foi acertada. O AHP permitiu converter as preferências humanas em valores numéricos, não sendo mais uma simples observação da realidade. O AHP, portanto, permitiu comparar e qualificar numericamente as preferências dos respondentes e depois chegar a resultados numéricos para cada um dos grupos. Também, nota-se que a qualidade das informações recebidas tende a ser mais assertiva, visto que o método garante a consistência das respostas. Não obstante a condição humana dos respondentes, o método, apesar de apontar inconsistências, tolera o limite de 10%, o que o torna uma ferramenta adequada para trabalhar com fatores onde a percepção humana, cheia de inconsistências, pode ser aceita e mensurada.

A Ferramenta criada para este trabalho implementa o método AHP. Seu uso foi fundamental para que o trabalho fosse executado, pois facilitou e acelerou a tomada de respostas. Parte desta aceleração é devido à análise da inconsistência, não permitindo que sejam enviadas respostas inconsistentes portanto, evitando que os pesquisadores tenham que voltar aos respondentes para ajustar as respostas.

Analisando o agrupamento das respostas, observamos que existe uma divergência bastante significativa entre os diversos níveis estudados. Comparando a visão do nível de gestão superior com os demais, podemos verificar que enquanto este nível valoriza a importância da dimensão liderança em detrimento das demais, O Nível gestor intermediário se aproxima mais do nível gestor superior, enquanto o nível gestor próximo por sua vez se aproxima do nível operacional.

Diante disto, é possível entender que as mensagens relativas à compreensão da importância das dimensões da inovação, oriundas do dos níveis superiores não tem sido adequadamente compreendido ou aceito pelos níveis operacional e nível gestor próximo.

Não é objeto deste trabalho entender as razões das divergências de opinião entre os diversos grupos, portanto, este levantamento poderia ser objeto de trabalhos futuros.

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Transición Energética: Interacciones estratégicas ante la redistribución (o no) de impuestos

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Abstract. The energy transition is a process that we can observe in the history of humanity because it generates a positive impact that such process has on the population's living standards. For example, humankind has evolved from heat energy produced by wood to autonomous planes powered by solar energy. Nowadays, the transition from fossil to renewable energy pursues the maintenance of a constant improvement rate on living standards without affecting the environment. However, the current development of renewable energy does not cover global demand for energy, and the adoption costs are too high for consumers and producers as well. Thus, it is necessary a driver intermediary that facilitates the current transition. In this paper, we analyze the role of the Government as a driver intermediary for the adoption and generation of renewable energy by consumers and producers. We model the interaction through as a three-stage game where the Government sets the public policy by imposing taxes and giving subsidies to the industry after the initial stage and fully implements them in two later stages where firms compete as in the Cournot's model.

Keywords: Energy Transition, Driver Intermediary, Sub-game Perfect Nash equilibrium.

1 Introducción

En la última década, la temperatura global ha alcanzado niveles superiores a los de la época pre-industrial lo cual ha generado cambios climáticos, pérdida de ecosistemas y problemas de salud pública (Jackson et al., 2018). Debido al impacto de los gases de efecto invernadero en el incremento de la temperatura mundial, la comunidad internacional firmó el Acuerdo de París en el año 2015 con el objetivo de reducir la emisión de dichos gases (IPCC, 2018). Particularmente, los países firmantes se comprometieron a transitar hacia actividades menos contaminantes basadas en energía renovables (Hoegh-Guldberg et al., 2018).

Se conoce como Transición Energética (TE) al proceso de sustitución de fuentes de energía no renovables, como los combustibles fósiles, por fuentes de energía renovables para la generación de calor, movimiento y luz (Smil, 2010). Dados los costos asociados a dicho proceso, la comunidad internacional presenta avances heterogéneos

al respecto. Por ejemplo, los países en desarrollo no tienen recursos suficientes para desarrollar estrategias de transición energética. Sin embargo, es necesario implementar políticas públicas que aceleren dicho proceso debido a la posible irreversibilidad del cambio climático y los fenómenos que puede generar.

El presente trabajo estudia como la redistribución fiscal influye en las decisiones del oligopolio energético durante la TE. Puesto que en dicho proceso empresas y gobierno son agentes estratégicos (Loorbach et al., 2008), modelamos la transición energética tomando como base el juego de Suárez y Gibaja (2019). En el presente artículo, nos enfocamos en analizar las decisiones de las empresas cuando el gobierno implementa, o no, una política redistributiva en la tercera etapa de los ingresos fiscales obtenidos mediante impuestos durante la segunda etapa. También, analizamos el impacto de las estrategias de política pública considerando diferentes estructuras de mercado.

El presente trabajo se relaciona de manera estrecha con la literatura que reconoce los conflictos que pueden emerger en un proceso cuyo éxito depende de la cooperación de los agentes (Bridge et al., 2013). Así, la modelación de la TE parte de la interacción gobierno-empresa como un juego en el que la decisión de un agente afecta el resultado del otro (Pérez et al., 2004); es decir, soluciones cooperativas y no cooperativas dentro de los patrones de decisión de los agentes involucrados son relevantes para estudiar la adopción de nuevos productos e insumos. En este sentido, Weitzman (1993) explica las diferencias en las transiciones económicas de países comunistas hacia modelos de libre mercado a partir de la cooperación social, la cual emerge de las interacciones repetidas (Teorema del Folk).

Entre nuestras contribuciones, destaca el análisis que hacemos del gobierno como "agente conductor" de la TE. Autores como (Van Veurden, 2017) reconocen la necesidad de establecer este tipo de agentes para generar incentivos para adoptar nuevas tecnologías e insumos. Específicamente, asumios que el gobierno interviene en este proceso para evitar fallos que afecten negativamente el bienestar social durante la TE.

La competencia tipo Cournot es la base de nuestro modelo pues los mercados energéticos se caracterizan por el intercambio de bienes homogéneos en un contexto oligopólico (Borenstein et al., 1999; Ludkovski & Sircar, 2015; Villar & Rudnick, 2002). En esta rama de la literatura, el análisis de juegos se enfoca en establecer políticas regulatorias para mantener estables los precios de un insumo esencial para las actividades económicas. Nuestro principal resultado indica que, a pesar de las estructuras de costos, es posible desarrollar una transición exitosa cuando el gobierno impone impuestos en una primera etapa y después los distribuye como subsidios. Sin embargo, el considerar un espacio de acciones discreto también genera escenarios donde los agentes prefieren una estrategia mixta a una estrategia pura; es decir, la energía renovable no sustituye totalmente a la energía no renovable debido a la posible falta de cooperación de las empresas.

El artículo se encuentra estructurado de la siguiente manera. La sección 2 detalla el modelo matemático que proponemos para analizar las políticas públicas de transición energética.

2 Modelo

En esencia, el proceso de TE busca sustituir insumos que generen una gran cantidad de gases de efecto invernadero por fuentes generación de energía más limpias. Sin embargo, el éxito de la TE recae en la disposición de los agentes para cambiar sus esquemas de producción y consumo de energía. Particularmente, las empresas energéticas son renuentes a llevar cabo dicho proceso pues los insumos tradicionales les generan economías de escala (Nicholson & Snyder, 2015). Lo anterior genera barreras de entrada a otras empresas lo que permite el surgimiento de oligopolios energéticos.

Se sabe que la energía es homogénea en dichos mercados, por lo que es usual estudiar las interacciones en los mercados energéticos por medio del modelo de Cournot (Ludkovski & Sircar, 2015; Pérez et al., 2004). Con respecto a la TE, Suárez y Gibaja (2019) proponen un modelo de TE basado en la repetición del juego de Cournot añadiendo la intervención del gobierno en una primera etapa.

En el presente trabajo, consideremos una versión discreta del modelo de Suárez y Gibaja (2019) enfocada en la total redistribución, o no, de recursos fiscales. Dicha variación se describe en las siguientes subsecciones.

2.1 Elementos básicos del juego

Consideramos un mercado energético en el que el gobierno establece una política pública que busca incentivar la producción de energía mediante fuentes renovables. Denotamos por g al gobierno, y por F al conjunto de firmas productoras de energía. Por simplicidad, consideramos que $F = \{e_1, e_2\}$, donde e_i representa una firma genérica. Puesto que los consumidores no distinguen entre energía proveniente de combustibles fósiles o renovables, asumimos que los consumidores no son agentes estratégicos. Entonces, el conjunto de agentes estratégicos es $S = \{g\} \cup F$.

Cada empresa $e_i \in F$ produce energía usando insumos renovables (r) o no renovables (f). Sea $R = \{r, f\}$ el conjunto de insumos disponibles para producir energía. Denotamos por q_i^p la energía que produce e_i utilizando un insumo $p \in R$. Entonces, la producción total de energía de la firma e_i es $q_i = q_i^r + q_i^f$, mientras que $\overline{q_i} = \left(q_i^r, q_i^f\right)$ representa el plan de producción de e_i. También, consideramos que e_i tiene una función de costos C_i que depende de $\overline{q_i}$. Puesto que estamos buscando genera una TE, asumimos costos separables por las características de la energía renovable y no renovable. Así, $C_i = c_i^r \cdot q_i^r + c_i^f \cdot q_i^f$ donde c_i^p es el costo marginal de que i utilice el insumo p. Además, consideramos que $c_i^r > c_i^f$ pues producir energía con fuentes renovables es más costoso que hacerlo con fuentes no renovables debido a las economías de escala existentes en los mercados energéticos (Nicholson & Snyder, 2015).

Se asume que el gobierno es el "agente conductor" que define la política pública para incentivar la TE. Denotamos por $v = (\sigma, \tau)$ la política pública del gobierno, donde σ es un subsidio a la producción de energía con insumos renovables, mientras que τ es un impuesto al uso de combustibles fósiles.

Los consumidores demandan una cantidad total de energía $Q = Q_f + Q_r$, donde Q_f es la demanda que se cubre con insumos no renovables y Q_r es la energía que se pro-

duce con fuentes renovables. Sea P_j el precio de la energía que se produce utilizando el insumo $j \in R$.

2.2 El juego de la transición energética

Definimos el juego de la Transición Energética como un conflicto estratégico en el que intervienen los agentes en F, mientras que los consumidores no son agentes estratégicos pues no distinguen entre energía renovable y no renovable. La interacción entre gobierno y empresas se modela como un juego de tres etapas a través del cual se busca la sustitución de combustibles fósiles por combustibles más limpios mediante la intervención del gobierno. , en el cual el gobierno puede escoger entre definir una política pública no redistributiva en la cual solo implementará un impuesto al consumo que será aplicado en la etapa 2 o puede optar por una política de tipo redistributivo en la cual define un impuesto al consumo que implementa en la etapa 2 y un subsidio a la producción con fuentes renovables que implementa en una etapa 3 y que se financia a través del recaudo fiscal de la etapa 2. Considerando lo anterior se demarca que $T = \{1,2,3\}$ es el conjunto de las etapas del juego, en donde t denota una etapa genérica en el mismo, para efectos de notación explicativa se tendrá que (q_i^{tr}, q_i^{tf}) denota la producción de una firma e_i en un momento t del juego, a continuación se desglosa el desarrollo general de las etapas considerando las variantes de decisión del gobierno partiendo del escenario base de política pública redistributiva (PPR) a partir de la cual se deduce la variante no redistributiva (PPNR) :

Etapa 1: El gobierno g define una política pública (τ,σ) en la cual τ es un impuesto a la cantidad consumida de Q_f, y σ es un subsidio directo a la cantidad producida de Q_r. Se asume que el gobierno en esta etapa anuncia de manera publica su determinación y por lo tanto consumidores y productores con conocedores del tipo de medida y su momento de aplicación.

Etapa 2: Los consumidores y productores son conocedores de la medida del gobierno, y el gobierno pone en marcha un impuesto a la cantidad (τ) consumida de energía producida a través de fuentes no renovables. Todas las firmas del conjunto F observan la demanda de energía y determinan su plan de producción $q_i^2 = (q_i^{2r}, q_i^{2f})$ de manera simultánea en un marco de competencia por cantidad. Se asumen que en esta etapa aún no se da la transición y las empresas siguen produciendo un 100% de energía a través de fuentes no renovables.

Etapa 3: En la etapa 2 el gobierno obtiene un recaudo fiscal τ*O por medio del cual financia el subsidio σ para la producción de Q_r para cada firma e_i. Al igual que en la etapa anterior, todas las firmas competirán por cantidades a través de la elección simultanea de su plan de producción $q_i^3 = (q_i^{3r}, q_i^{3f})$, se asume que en esta última etapa se da la transición energética y se produce un 100% de energía a través de fuentes renovables.

La estructura del juego por etapas da cuenta del papel de "agente conductor" que lleva a cabo el gobierno, el cual a partir de un impuesto y un subsidio busca generar estímulos para la transición energética, se asume que la información es de carácter público cuando proviene del gobierno por lo tanto en la etapa de definición se informa

y en las etapas de implementación se hacen efectivas las medidas en las etapas 2 y 3 respectivamente. En el momento en que las firmas comienzan a tomar decisiones se asume que siempre decidirán simultáneamente y competirán por cantidades, por lo tanto, en las etapas 2 y 3 las firmas mantienen un estilo de competencia Cournot influidas por las medidas del gobierno dando lugar a que en el momento 2 preserven su producción a partir de fósiles y en el momento 3 pasen a una producción con fuentes renovables.

Se considera que, dentro de las posibilidades de decisión del gobierno, este también puede optar por una política pública de carácter "no redistributivo" en donde únicamente aplica un impuesto al consumo (τ), para este caso se mantiene una dinámica casi idéntica, no obstante, ante una política de este tipo dadas las condiciones de alto costo que implica pasar a la producción de energía con fuentes renovables las empresas no tendrán ningún incentivo para cambiar sus planes de producción, el único efecto esperado es un aumento de precio impulsado por el gravamen y un efecto transitorio sobre la demanda que seguirá prefiriendo el consumo de Q_f, se asume así que en el marco de una política no redistributiva el impuesto será internalizado y no habrá una transición, así las cosas, ante la decisión en el momento 1 de implementar un impuesto, se llegará únicamente a la etapa dos en donde las firmas compiten por cantidades eligiendo de manera simultánea su plan de producción que seguirá siendo dirigido a la producción a partir de fuentes no renovables. Al final de este tramo el gobierno tendrá un recaudo fiscal τ*O que no será usado para invertir en la transición; en este caso la TE se considera fallida deteniéndose en la etapa 2.

Finalmente, es importante resaltar que las empresas e_1 y e_2 en términos genéricos tienen un conjunto de acciones básicas respectivamente en donde pueden optar por una producción máxima (Max) o mínima (Min), tales acciones demarcan las variantes estratégicas de las firmas en medio de un marco de competencia ya descrito. En una sección posterior del desarrollo del juego se demarcarán algunas condiciones adicionales y necesarias para acotar el espacio de decisión a un espacio discreto, por el momento su simple demarcación es suficiente para representar el juego en su forma extensiva.

Demarcado todo lo anterior, a continuación, se procede a representar de manera general la estructura del juego de la transición energética con el fin de conocer la estructura de los nodos de decisión y lograr ver de manera gráfica las especificaciones formales desarrolladas, es preciso aclarar que esta primera representación no pretende mostrar una solución del juego, únicamente busca dejarlo descrito para posteriormente continuar especificando las condiciones para determinar los pagos y conocer posteriormente el equilibrio. La representación extensiva del juego se muestra en la Fig. 1.

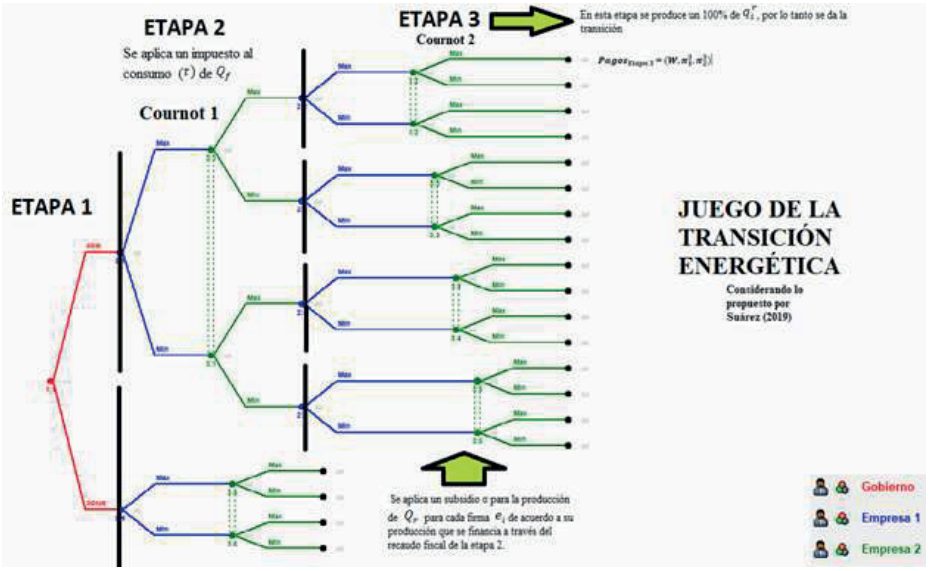

Fig. 1. Representación extensiva del juego de la transición energética considerando lo propuesto por Suarez (2019). Elaboración propia a partir del software de libre distribución Gambit 2015.

La representación extensiva del juego permite visualizar la estructura dinámica del juego. Es decir, se trata de un juego de tres etapas con información completa en el que los jugadores observan las acciones que hace cada uno de los otros jugadores. Los nodos terminales muestran los pagos en los que se resume el impacto del subsidio y de los impuestos de acuerdo con las etapas en las que son aplicados.

Al ser un juego por etapas, el equilibrio de Nash no es un concepto de solución deseable ya que permite la generación de amenazas no creíbles. Para evitar lo anterior, utilizamos como concepto de solución el Equilibrio de Nash Perfecto en Subjuegos (ENPS).

Un **Equilibrio de Nash Perfecto en Subjuegos** es un perfil de estrategias $\left((\tau^*, \sigma^*), (q_1^{1*}, q_1^{2*}), (q_2^{1*}, q_2^{2*})\right)$ que conforma un equilibrio de Nash en cada subjuego inducido por el juego descrito en la sección previa.

3 Análisis de equilibrio

El concepto de solución con el que se analiza el juego de la TE es el equilibrio de Nash Perfecto en Subjuegos. Para determinar los ENPS de la interacción entre gobierno y empresas, procedemos por inducción hacia atrás. Sin embargo, es necesario establecer los pagos que cada uno de los agentes obtiene al término del juego; a continuación describimos los parámetros (ingresos, costos, beneficios, impuestos y subsidios) que se utilizan para poder realizar el cálculo delos ENPS.

3.1 Desarrollo del juego

Los valores que se utilizan para obtener los pagos de los jugadores se construyen con base en los supuestos del modelo de Cournot. Es decir, se asume una función de costos que refleja la diferencia entre los ingresos y el costo. Además, se considera una demanda inversa lineal que depende de las acciones de las empresas generadores de energía, mientras que los costos marginales se ven impactados por la política pública implementada en cada una de las etapas del juego. A su vez se considera que la única vía para la reducción o aumento temporal de la demanda es la imposición de un impuesto o un subsidio por lo que la variación inducida por las intervenciones es independiente de las variaciones inducidas por la oferta.

Los parámetros básicos para obtener la demanda que enfrentan las empresas en cada una de las etapas son:

- En la etapa 2 se aplica un impuesto de 10 unidades monetarias (u.m) añadidas al precio de la energía fósil. Se considera que Q_f es 140 unidades energéticas (u.e). Puesto que en la etapa no se ha alcanzado la TE, se tiene que $P_f < P_r$; por consiguiente, $Q = Q_f$ y $Q_r = 0$. Es decir, los planes de producción q_i^2 son dominados por q_i^{2f} pues q_i^{2r}=0 para ambas firmas.
- En la etapa 3 se implementa un subsidio de 10 u.m a la producción Q_r , cuyo valor es de 150 u.e. Puesto que el impuesto sobre Q_f sigue activo, la implementación del subsidio implica que $P_f > P_r$. También, sabemos que las preferencias de los consumidores corresponden a un patrón de sustitución perfecta; esto implica que $Q = Q_r$ y $Q_f = 0$. Es decir, nos encontramos en un escenario de transición energética completa en el que los planes de producción q_i^3 están dominados por q_i^{3r} ya que q_i^{3f}=0 para ambas firmas.

Dadas las demandas básicas para cada una de las etapas, la fluctuación de precios se describe a continuación:

- Si $O = Q$, entonces el precio de referencia para P_f o P_r se mantiene igual al precio inicial de etapa.
- Si $O = Q$ + 10 u.e entonces hay sobreoferta. En consecuencia, se determina que por cada 10 unidades por encima de la demanda del mercado habrá una disminución de 4 u.m en el precio de referencia del tipo de energía demandado.
- Si $O = Q - 10$ u.e se genera escasez. Entonces, por cada 10 unidades por debajo de la demanda del mercado habrá un aumento de 4 u.m en el precio de referencia del tipo de energía demandado.

En otras palabras, las empresas productoras de energía tienen la capacidad de controlar los precios de energía. Por consiguiente, los consumidores toman decisiones racionalmente y no estratégicamente; es decir, los consumidores observan precios y buscan el consumo de energía que maximice su utilidad.

Puesto que el mercado energético que consideramos es un duopolio, la oferta que es generada por las empresas puede estar desequilibraba respecto a la demanda. Entonces, es necesario definir el espacio de decisión de las firmas.

Primero consideramos una situación en la que la producción es asimétrica y el mercado está vigilado por el gobierno. Dicho en otras palabras, el gobierno aplica una política regulatoria activa para el otorgamiento de subsidios e imposición de impuestos. Así, consideramos que las firmas tienen un espacio de decisión discreto, en donde el conjunto de las acciones de la empresa e_1 es E_1=$\{Max_{e1}, Min_{e1}\}$ y el conjunto de las acciones de e_2 es E_2=$\{Max_{e2}, Min_{e2}\}$; donde Max y Min cumplen la función de parámetros de producción que dependen del tamaño que se asuma para las firmas en términos de producción y que además se comportan como parámetros de expectativa. Es decir, estos valores representan la cooperación y no cooperación de las empresas para producir energía renovable. De manera análoga al Dilema del Prisionero, las mejores respuestas de las empresas se pueden describir de la siguiente manera:

- Si e_1 produce Max esperando que e_2 produzca Max entonces e_2 producirá Max esperando que e_1 produzca Max.
- Si e_1 produce Max esperando que e_2 produzca Min entonces e_2 producirá Min esperando que e_1 produzca Max.
- Si e_1 produce Min esperando que e_2 produzca Max entonces e_2 producirá Max esperando que e_1 produzca Min.
- Si e_1 produce Min esperando que e_2 produzca Min entonces e_2 producirá Min esperando que e_1 produzca Min.

Los espacios de acciones anteriores generan cuatro escenarios. En otras palabras, la transición energéticos, considerando un espacio de decisiones discreto, se limita al análisis de los escenarios Cooperar-Cooperar, Cooperar-No cooperar, No cooperar-Cooperar, y No cooperar- No cooperar. La Tabla 1 resume las acciones, pagos y características de equilibrio de cada uno de los escenarios anteriores

Tabla 1 Perfiles de decisión discreta para las firmas en el juego de la transición energética- Empresas con producción asimétrica y mercado vigilado. Elaboración propia.

Características del Mercado en la Etapa 2.						
Est. e1	Est. e2	Prod. e1	Prod. e2	Prod. total	Demanda total	Situación
Max	Max	85	65	150	140	Sobre-oferta
Max	Min	80	60	140	140	Equilibrio
Min	Max	60	80	140	140	Equilibrio
Min	Min	70	70	140	140	Equilibrio

Características del Mercado en la Etapa 3.						
Est. e1	Est. e2	Prod.	Prod. e2	Prod.	Demanda	Situación

		e1		total	total	
Max	Max	90	70	160	150	Sobre-oferta
Max	Min	90	60	150	150	Equilibrio
Min	Max	60	90	150	150	Equilibrio
Min	Min	75	75	150	150	Equilibrio

La Tabla 1 presente la estructura general del mercado (oferta y demanda), la cual es necesaria para la obtención de precios por medio de la demanda inversa lineal. Ahora, procedemos a describir los costos, que son necesarios para el cálculo del beneficio que obtienen las empresas cuando la interacción termina.

Consideramos que $c_i^f = 30$ y $c_i^r = 40$ en todas las etapas. El beneficio para la etapa 2 se calcula como $\pi_i^2 = (P_r^2 q_i^{2r} + P_f^2 q_i^{2f}) - (c_i^f q_i^{2f} + q_i^{2r} c_i^r + q_i^{2f} \tau)$. Puesto que $q_i^{2r} = 0$, podemos simplificar el beneficio a $\pi_i^2 = P_f^2 q_i^{2f} - (c_i^f q_i^{2f} + q_i^{2f} \tau)$. Por otro lado, sabemos que subsidio da lugar a un precio compensado pagado al productor durante la etapa tres; es decir, tenemos que $\pi_i^3 = P_{r\sigma}^3 q_i^{2r} - c_i^r q_i^{2r}$ ya que $q_i^{3f} = 0$.

En lo que respecta al gobierno, éste optar por una política pública redistributiva (PPR) o una política pública no redistributiva (PPNR). La PPR aplica tanto un impuesto a la energía fósil como un subsidio a la producción de energía renovable, respecto a los cuales se mantiene un presupuesto equilibrado. En otras palabras, el recaudo fiscal financia al subsidio para que el gobierno no incurra en deuda para aplicar su política. Por otro lado, al aplicar la PPNR, el gobierno no hará ningún tipo de redistribución para la producción de energía renovable y destinará el recaudo fiscal para otros fines.

En términos concretos, se considera que el impuesto al consumo Q_f será de 10 u.m por unidades energéticas. Por lo tanto, en la etapa 2 el precio de referencia de la energía de fuentes no renovables se incrementa en tal valor. Por otro lado, el subsidio se define como $\sigma = \frac{O^t}{O^{t-1}\tau}$; entonces, la oferta de la etapa 3 se divide por el total del recaudo fiscal de la etapa 2. Lo anterior asegura la condición de presupuesto equilibrado para el gobierno.

Además, es importante recordar que el gobierno juega un papel de "dictador benevolente" que busca maximizar su función de bienestar social. Esta última está dada por W= $\sum_{i=1}^{2} \pi_i^2 + \sum_{i=1}^{2} \pi_i^3$, es decir, el gobierno mide el bienestar de las empresas de manera utilitaria. La Fig. 2 resume los pagos del gobierno y las empresas cuando consideramos los diferentes valores establecidos para producción mínima, máxima, costos, impuestos y subsidios.



Comportamiento de los precios por etapa según las decisiones tomadas por las firmas							
ETAPA 1	Estrategias (E2[e1,e2]) y E3[e1,e2]]	Precios sin intervención		ETAPA 2		ETAPA 3 -SUBSIDIO-	
		Precio Qf (u.m)	Precio Qr (u.m)	Precio con impuesto a Qf (u.m)	Subsidio unitario para E2 a Qr (u.m)	Precio pagado al productor Qr (u.m)	Precio percibido por el consumidor Qr (u.m)
GOBIERNO OPTA POR PPR	Max, Max y Max, Max	39	50	46	8,38	50,38	42
	Max, Max y Max, Min			45	10,00	55	40
	Max, Max y Min, Max			45	10,00	55	40
	Max, Max y Min, Min			46	10,00	55	40
	Max, Min y Max, Max			49	8,75	48,75	42
	Max, Min y Max, Min			49	9,33	54,33	40
	Max, Min y Min, Max			49	9,33	54,33	40
	Max, Min y Min, Min			49	9,33	54,33	40
	Min, Max y Max, Max			49	8,75	48,75	42
	Min, Max y Max, Min			49	9,33	54,33	40
	Min, Max y Min, Max			49	9,33	54,33	40
	Min, Max y Min, Min			49	9,33	54,33	40
	Min, Min y Max, Max			49	8,75	48,75	42
	Min, Min y Max, Min			49	9,33	54,33	40
	Min, Min y Min, Max			49	9,33	54,33	40
	Min, Min y Min, Min			49	9,33	54,33	40
GOBIERNO OPTA POR PPNR	Max y Max			46	NO APLICA- EL GOBIERNO NO APLICA SUBSIDIO		
	Max y Min			45			
	Min y Max			45			
	Min y Min			46			

Fig. 2 Comportamiento de los precios por etapa según las decisiones tomadas por las firmas. Tabla de elaboración propia a partir de cálculos de los autores

Los aspectos señalados son suficientes para la definición de los pagos que perciben los agentes en cada uno de sus perfiles de estrategias y a lo largo de las etapas. En cada uno de los perfiles estrategicos que pueden desarrollarse, se define que los pagos corresponderán a b =(W, π_1^t, π_2^t), considerando la Ilustración 1 se sabe que del primer Cournot correspondiente a la segunda etapa en el nodo de decisión PPR tendrá 4 vectores de pagos, y del segundo Cournot se derivaran 16 vectores de pagos, a su vez del nodo de decisión PPNR únicamente se derivaran 4 vectores de pagos que pertenecen a la segunda etapa. En la tabla que se presenta a continuación se da cuenta de los pagos desglosados por cada uno los posibles perfiles estratégicos de las firmas:



Pagos de los agentes por cada conjunto de estatregias									
		Estrategias (E2[e1,e2]) y E3[e1,e2]]	ETAPA 2		ETAPA 1		Pagos Finales e1 y e2		Bienestar Utilitario (W)
			e1	e2	e1	e2	e1	e2	
GOBIERNO OPTA POR PPR	RF=Qf=1500	Max, Max y Max, Max	425	325	843,75	656,25	1268,75	981,25	2250
		Max, Max y Max, Min	425	325	1260	840	1685	1165	2850
		Max, Max y Min, Max	425	325	900	1350	1325	1675	3000
		Max, Max y Min, Min	425	325	1050	1050	1475	1375	2850
	RFxQFx2400	Max, Min y Max, Max	720	540	787,5	612,5	1507,5	1152,5	2660
		Max, Min y Max, Min	720	540	1200	800	1920	1340	3260
		Max, Min y Min, Max	720	540	800	1200	1520	1740	3260
		Max, Min y Min, Min	720	540	1000	1000	1720	1540	3260
	RFxQFx1400	Min, Max y Max, Max	540	720	787,5	612,5	1327,5	1332,5	2660
		Min, Max y Max, Min	540	720	1200	800	1740	1520	3260
		Min, Max y Min, Max	540	720	800	1200	1340	1920	3260
		Min, Max y Min, Min	540	720	1000	1000	1540	1720	3260
	RFxQFx1400	Min, Min y Max, Max	630	630	787,5	612,5	1417,5	1242,5	2660
		Min, Min y Max, Min	630	630	1200	800	1830	1430	3260
		Min, Min y Min, Max	630	630	800	1200	1430	1830	3260
		Min, Min y Min, Min	630	630	1000	1000	1630	1630	3260
GOBIERNO OPTA POR PPNR	RF=1500	Max y Max	425	325	El gobierno no redistribuye el recaudo fiscal		425	325	750
	RF=1400	Max y Min	720	540			720	540	1260
	RF=1400	Min y Max	540	720			540	720	1260
	RF=1400	Min y Min	630	630			630	630	1260

RF= Recaudo Fiscal - Qf= Gasto fiscal - El gobierno opta por un presupuesto equilibrado

Fig. 3 Pagos de los agentes por cada conjunto de estrategias. Tabla de elaboración propia a partir de cálculos de los autores.

3.2 Resolución del juego

Como bien se ha mencionado con anterioridad el juego de la transición energética aquí planteado es de carácter dinámico y cuenta con información completa, por lo tanto, el concepto de solución por el cual se opta es el Equilibrio de Nash Perfecto en Sub Juegos para el cual se aplica el algoritmo de inducción hacia atrás para poder llegar al concepto de solución general para el cual debe cumplirse que todos los sub-

juegos que integran al juego general deben llegar a un equilibrio de Nash de modo que el equilibrio represente el perfil estratégico no cooperativo que conduzca a la maximización de los beneficios respecto a las decisiones de los otros agentes que intervienen.

Para hallar el ENPS se ha hecho uso del software Gambit 15 en el cual se han introducido los pagos calculados y consignados para cada momento del juego en la Tabla 3, para el hallar el equilibrio se ha hecho uso del método de solución recomendado por el software usando la representación extensiva1 para la cual se ha definido encontrar un solo equilibrio el cual en su marco ideal será un ENPS en estrategias puras.

Una vez se corre el modelo en Gambit 15 se puede apreciar que el juego dinámico de la transición energética bajo las condiciones de producción asimétrica y mercado vigilado cuenta con un ENPS en estrategias puras y pertenece al conjunto de estrategias del renglón 6 de la Tabla 3 en donde en forma descriptiva se tiene que:

Juego de la transición energetica - Equilibrio de Nash Perfecto en Subjuegos- Estrategias óptimas de los agentes				
Etapa 1	Etapa 2 - Cournot 1		Etapa 3 -Cournot 2	
Estrategia Optima del gobierno	Estrategia óptima e1	Estrategia óptima e2	Estrategia óptima e1	Estrategia óptima e2
PPR	Max	Min	Max	Min

Tabla 2 ENPS del juego de la transición energética - estrategias optimas de los agentes en el equilibrio en estrategias puras. Tabla de elaboración propia

- En la etapa 1 el gobierno opta por una PPR.
- En la etapa 2 e_1 opta por producir Max esperando que e_2 produzca Min y e_2 produce Min esperando que e_1 produzca Max siendo las decisiones de producción orientadas 100% a energía producida a partir de fuentes no renovables.
- En la etapa 3 e_1 opta por producir Max esperando que e_2 produzca Min y e_2 produce Min esperando que e_1 produzca Max siendo las decisiones de producción orientadas 100% a energía producida a partir de fuentes renovables.
- Dentro de las decisiones tomadas por los agentes en el ENPS hay una tendencia a mantener siempre el mercado en un estado O=Q por lo tanto en este estado óptimo se considera no conveniente alterar el equilibrio del mercado ya que hacerlo reporte menores beneficios para los agentes.

Al final del juego el vector de pagos para los agentes es *b= (3260,1920,1340)* y representa el vector de pagos óptimo para los agentes.

4 Variaciones de la interacción

La versión principal del juego en su versión discreta cuenta con dos variantes que son relevantes y que dan muestra de otros comportamientos posibles de las firmas y

[1] Para visualizar las representaciones extensivas del juego con los pagos asignados y la solución hallada por Gambit 15 puede dirigirse al Apéndice A en donde se encuentran las representaciones extensivas de las diferentes variantes del juego.

su solución de equilibrio cuando hay variaciones en la configuración de producción de las empresas y el grado de vigilancia del mercado en el que se mueven.

Las variantes que se consideran contemplan el escenario en el que las firmas presentan producciones de carácter simétrico, es decir, cuando se asume que en los niveles de estrategias Max-Max y Min-Min aportaran niveles iguales de producción y en donde además se juega con la "regulación" y "desregulación" del mercado frente a la posibilidad de generar escasez, para presentar las variantes se optará por un desarrollo simplificado en donde se hará énfasis en los cambios de cantidad producida en los perfiles de estrategia, fluctuación de precios y los pagos de los agentes, con el fin de mostrar la solución de equilibrio en cada uno de estos casos adicionales.

Es importante resaltar que las variantes del juego preservan la mayoría de supuestos y condiciones demarcadas en las secciones anteriores, en caso de presentarse alguna variación se aclarará de manera explícita al inicio del desarrollo de la variación con el fin de tener claridad.

La intención de mostrar las variantes del juego es alimentar la discusión respecto a los escenarios y rumbos que podría tomar la política pública aplicada por el gobierno, y como la estructura de producción del mercado y el nivel de vigilancia del mismo puede afectar de manera significativa el rumbo y resultados en términos de bienestar de la política.

4.1 Juego de la transición energética con empresas con producción simétrica y mercado no vigilado

Para esta variante del juego de la transición energética se preservan los mismos elementos básicos del juego, se preservan los parámetros de preferencia de los agentes, y la dinámica de interacción entre oferta y demanda y sus parámetros, los únicos cambios que se consideran son:

- Las empresas se mueven dentro de un mercado no vigilado en donde es posible generar sobre-oferta y también es posible generar escasez sin llegar a incurrir en algún tipo de sanción.
- Las empresas producen simétricamente en sus extremos de decisión Max-Max y Min-Min, por lo tanto, la posibilidad de generar sobre oferta traerá consigo que cada empresa produzca la mitad de la oferta total y lo mismo ocurrirá en el caso de que se genere escasez, se asume que los marcos de decisión se dan en forma simultánea y sin tener plena certeza de la producción de la otra firma siguiendo los supuestos del modelo Cournot bajo una dinámica de competencia por cantidades.

Considerando los cambios anteriores los perfiles de decisión de producción discreta para esta variante son:

Conjunto de posibilidades de producción en la etapa 2 - Variante con producción simétrica y mercado no vigilado						
Estrategia e1	Estrategia e2	Producción e1	Producción e2	O= Producción total	Q=Demanda basica del mercado	Situación de mercado
Max	Max	75	75	150	140	Sobre-oferta
Max	Min	80	60	140	140	Equilibrio
Min	Max	60	80	140	140	Equilibrio
Min	Min	65	65	130	140	Escasez
Conjunto de posibilidades de producción en la etapa 3- Variante con producción simétrica y mercado no vigilado						
Estrategia e1	Estrategia e2	Producción e1	Producción e2	O= Producción total	Q= Demanda basica del mercado	Situación de mercado
Max	Max	80	80	160	150	Sobre-oferta
Max	Min	90	60	150	150	Equilibrio
Min	Max	60	90	150	150	Equilibrio
Min	Min	70	70	140	150	Escasez

Tabla 3 Perfiles de decisión discreta para las firmas en el juego de la transición energética- Empresas con producción simétrica y mercado no vigilado. Elaboración propia

Como puede observarse dado que se eliminan las restricciones en este caso se presentan escenarios en los cuales se cumple que O>C y C>O, ante esto habrá mayor variabilidad en los precios, no obstante, en esta variante se mantienen los mismos precios de referencia sin intervención y a su vez se asume que el valor del impuesto al consumo y el mecanismo de asignación del subsidio es idéntico al utilizado para el juego principal, a continuación se muestra el comportamiento de los precios ante las diferentes variantes estratégicas teniendo en cuenta las condiciones preestablecidas para los casos en el que el mercado no se encuentra en equilibrio:

Comportamiento de los precios por etapa según las decisiones tomadas por las firmas - Variante con producción simetrica y mercado no vigilado							
ETAPA 1	Estrategias (E2[e1,e2] y E3[e1,e2])	Precios sin intervención		ETAPA 2	Subsidio unitario para E3 a Qr (u.m)	ETAPA 3	
		Precio Qf (u.m)	Precio Qr (u.m)	Precio con impuesto a Qf (u.m)		Precio pagado al productor Qr (u.m)	Precio percibido por el consumidor Qr (u.m)
GOBIERNO OPTA POR PPR	Max, Max y Max, Max	39	50	45	9,38	50,38	41
	Max, Max y Max, Min				10,00	55	45
	Max, Max y Min, Max				10,00	55	45
	Max, Max y Min, Min				10,71	59,71	49
	Max, Min y Max, Max			49	8,75	49,75	41
	Max, Min y Max, Min				9,33	54,33	45
	Max, Min y Min, Max				9,33	54,33	45
	Max, Min y Min, Min				10,00	59	49
	Min, Max y Max, Max			49	8,75	49,75	41
	Min, Max y Max, Min				9,33	54,33	45
	Min, Max y Min, Max				9,33	54,33	45
	Min, Max y Min, Min				10,00	59	49
	Min, Min y Max, Max			53	8,13	49,13	41
	Min, Min y Max, Min				8,67	53,67	45
	Min, Min y Min, Max				8,67	53,67	45
	Min, Min y Min, Min				9,29	58,29	49
GOBIERNO OPTA POR PPNR	Max y Max			45	NO APLICA- EL GOBIERNO NO APLICA SUBSIDIO		
	Max y Min			49			
	Min y Max			49			
	Min y Min			53			

Tabla 4 Comportamiento de los precios por etapa según las decisiones tomadas por las firmas –Variante con producción simétrica y mercado vigilado. Tabla de elaboración propia a partir de cálculos de los autores

Se asume que los pagos conservan la misma estructura del juego principal, por lo tanto los pagos para las firmas e_1 y e_2 serán equivalentes a sus beneficios individuales y el beneficio del gobierno continuará siendo igual a la sumatoria de los beneficios percibidos por las firmas, a continuación se muestran los pagos para esta variante del juego:

		Pagos del juego por cada conjunto de estatregias - Variante con producción simétrica y mercado no vigilado							
			ETAPA 2		ETAPA 3		pagos finales e1 y e2		Bienestar Utilitario (W)
		Estrategias (E2|e1,e2) y E3(e1,e2))	e1	e2	e1	e2	e1	e2	
GOBIERNO OPTA POR PPR	RF= GF=1500	Max, Max y Max, Max	375	375	750	750	1125	1125	2250
		Max, Max y Max, Min	375	375	1260	840	1635	1215	2850
		Max, Max y Min, Max	375	375	840	1260	1215	1635	2850
		Max, Max y Min, Min	375	375	1310	1310	1685	1685	3370
	RF=GF=1400	Max, Min y Max, Max	720	540	700	700	1420	1240	2660
		Max, Min y Max, Min	720	540	1200	800	1920	1340	3260
		Max, Min y Min, Max	720	540	800	1200	1520	1740	3260
		Max, Min y Min, Min	720	540	1260	1260	1980	1800	3780
	RF=GF=1400	Min, Max y Max, Max	540	720	700	700	1240	1420	2660
		Min, Max y Max, Min	540	720	1200	800	1740	1520	3260
		Min, Max y Min, Max	540	720	800	1200	1340	1920	3260
		Min, Max y Min, Min	540	720	1260	1260	1800	1980	**3780**
	RF=GF= 1300	Min, Min y Max, Max	845	845	650	650	1495	1495	2990
		Min, Min y Max, Min	845	845	1140	760	1985	1605	3590
		Min, Min y Min, Max	845	845	760	1140	1605	1985	3590
		Min, Min y Min, Min	845	845	1210	1210	2055	2055	4110
GOBIERNO OPTA POR PPNR	RF= 1500	Max y Max	375	375	El gobierno no redistribuye el recaudo fiscal		375	375	750
	RF= 1400	Max y Min	720	540			720	540	1260
	RF= 1400	Min y Max	540	720			540	720	1260
	RF= 1300	Min y Min	845	845			845	845	1690

Tabla 5 Pagos de los agentes por cada conjunto de estrategias en una variante con producción simétrica y mercado no vigilado. Tabla de elaboración propia a partir de cálculos de los autores.

Al igual que para el juego principal en este caso se introducen los valores de los pagos de los agentes en la representación extensiva del juego en el software Gambit 15 con el fin de hallar el ENPS, en esta ocasión nuevamente se usa el método recomendado por el software y a partir de él se obtiene que el juego cuenta con un ENPS en estrategias puras que corresponde al conjunto de estrategias de la Tabla 7 en el primer bloque en el renglón 16 en donde descriptivamente se tiene que:

Juego de la transición energetica - Equilibrio de Nash Perfecto en Subjuegos- Estrategias óptimas de los agentes - Variante con producción simétrica y mercado no vigilado				
Etapa 1	Etapa 2 - Cournot 1		Etapa 3 -Cournot 2	
Estrategia Optima del gobierno	Estrategia óptima e1	Estrategia óptima e2	Estrategia óptima e1	Estrategia óptima e2
PPR	Min	Min	Min	Min

Tabla 6 ENPS del juego de la transición energética en su variante con producción simétrica y mercado no vigilado - estrategias optimas de los agentes en el equilibrio en estrategias puras

- En la etapa 1 el gobierno opta por una PPR
- En la etapa 2 e_1 opta por producir Min esperando que e_2 produzca Min y e_2 produce Min esperando que e_1 produzca Min siendo las decisiones de producción orientadas 100% a energía producida a partir de fuentes no renovables.
- En la etapa 3 e_1 opta por producir Min esperando que e_2 produzca Min y e_2 produce Min esperando que e_1 produzca Min siendo las decisiones de producción orientadas 100% a energía producida a partir de fuentes renovables.
- Dentro de las decisiones tomadas por los agentes en el ENPS hay una tendencia a mantener siempre el mercado en un estado O<Q por lo tanto en este estado óptimo las empresas en su decisión simultanea tienden a producir cantidades bajas en aras de inducir escasez y llevar a un incremento en el precio

de la energía tanto proveniente de fuentes fósiles como de fuentes renovables.

- Al final del juego el vector de pagos para los agentes es b= (4110,2055,2055) y representa el vector de pagos óptimo para los agentes

4.2 Juego de la transición energética con empresas con producción simétrica y mercado vigilado

Para esta variante del juego de la transición energética se preservan los mismos elementos básicos del juego, preferencias de los agentes e interacciones entre oferta y demanda, los únicos cambios son el retorno al supuesto de mercado vigilado del juego principal en donde no es posible generar escasez, por otro lado se conserva el supuesto de producción simétrica de la primer variante, considerando en este caso que Min-Min corresponde a una decisión de producción en que las firmas producen la mitad de la demanda del mercado dado que no es posible producir por debajo de tal valor dada la vigilancia, a su vez dada su simetría en el caso Max-Max también producirán la mitad de la producción total.

Considerando lo anterior los perfiles de decisión de producción para las firmas en esta variante son:

Conjunto de posibilidades de producción en la etapa 2 -Variante con producción simétrica y mercado vigilado						
Estrategia e1	**Estrategia e2**	**Producción e1**	**Producción e2**	**O= Producción total**	**Q=Demanda basica del mercado**	**Situación de**
Max	Max	75	75	150	140	Sobre-oferta
Max	Min	80	60	140	140	Equilibrio
Min	Max	60	80	140	140	Equilibrio
Min	Min	70	70	140	140	Equilibrio
Conjunto de posibilidades de producción en la etapa 3 - Variante con producción simétrica y mercado vigilado						
Estrategia e1	**Estrategia e2**	**Producción e1**	**Producción e2**	**O= Producción total**	**Q= Demanda basica del mercado**	**Situación de**
Max	Max	80	80	160	150	Sobre-oferta
Max	Min	90	60	150	150	Equilibrio
Min	Max	60	90	150	150	Equilibrio
Min	Min	75	75	150	150	Equilibrio

Tabla 7 Perfiles de decisión discreta para las firmas en el juego de la transición energética- Empresas con producción simétrica y mercado vigilado. Elaboración propia

Dado que en esta variante nuevamente se tiene el supuesto de mercado vigilado solo existe un escenario en donde la oferta difiere de la demanda, considerando que se han mantenido los mismos precios de referencia sin intervención, para este caso la tabla de variación de precios será idéntica a la Tabla 2 dado que el único escenario de perturbación se da cuando las empresas deciden producir Max-Max, así las cosas, las únicas diferencias se darán en los pagos dado que ahora en los perfiles Max-Max y Min-Min la producción de las firmas resulta ser simétrica, a continuación se presentan los pagos para esta variante del juego:

		Pagos del juego por cada conjunto de estatregias - Variante con producción simétrica y mercado vigilado							
			M1		M2		Final		Bienestar
		Estrategias	E1	E2	E1	E2	E1	E2	Utilitario
GOBIERNO OPTA POR PPR	GF=1500	Max, Max y Max, Max	375	375	750	750	1125	1125	2250
		Max, Max y Max, Min	375	375	1260	840	1635	1215	2850
		Max, Max y Min, Max	375	375	840	1260	1215	1635	2850
		Max, Max y Min, Min	375	375	1050	1050	1425	1425	2850
	GF=1400	Max, Min y Max, Max	720	540	700	700	1420	1240	2660
		Max, Min y Max, Min	720	540	1200	800	1920	1340	3260
		Max, Min y Min, Max	720	540	800	1200	1520	1740	3260
		Max, Min y Min, Min	720	540	1000	1000	1720	1540	3260
	GF=1400	Min, Max y Max, Max	540	720	700	700	1240	1420	2660
		Min, Max y Max, Min	540	720	1200	800	1740	1520	3260
		Min, Max y Min, Max	540	720	800	1200	1340	1920	3260
		Min, Max y Min, Min	540	720	1000	1000	1540	1720	3260
	GF=1400	Min, Min y Max, Max	630	630	700	700	1330	1330	2660
		Min, Min y Max, Min	630	630	1200	800	1830	1430	3260
		Min, Min y Min, Max	630	630	800	1200	1430	1830	3260
		Min, Min y Min, Min	630	630	1000	1000	1630	1630	3260
GOBIERNO OPTA POR PPNR	RF= 1500	Max y Max	375	375	El Gobierno no redistribuye el recaudo fiscal		375	375	750
	RF= 1400	Max y Min	720	540			720	540	1260
	RF=1400	Min y Max	540	720			540	720	1260
	RF= 1400	Min y Min	630	630			630	630	1260

Tabla 8 Pagos de los agentes por cada conjunto de estrategias en una variante con producción simétrica y mercado vigilado. Tabla de elaboración propia a partir de cálculos de los autores

Para esta variante del juego, al computar el valor de los pagos en Gambit 15 se halla que no hay un ENPS en estrategias puras para esta versión del juego, por lo tanto, se obtiene un equilibrio en estrategias mixtas en el cual se asume que los agentes escogen entre varias posibles estrategias puras a los cuales se les asigna una probabilidad de ocurrencia lo cual equivale a un escenario de decisión tipo lotería, en este caso los perfiles de estrategias que evidencian mayores probabilidades se muestran y describen a continuación:

	Juego de la transición energetica - Equilibrio de Nash Perfecto en Subjuegos en estrategias mixtas- Estrategias óptimas de los agentes con mayor probabilidad de ocurrecia - Variante con producción simétrica y mercado vigilado				
	Etapa 1	Etapa 2 - Cournot 1		Etapa 3 -Cournot 2	
	Estrategia Optima del gobierno	Estrategia óptima e1	Estrategia óptima e2	Estrategia óptima e1	Estrategia óptima e2
Perfil estrategico 1	PPR	Min	Min	Max	Max
Perfil estrategico 2	PPR	Max	Min	Min	Min
Probabilidad asociada Perfil 1	1	0,5884	0,5884	0,6667	0,6667
Probabilidad asociada Perfil 2	1	0,4116	0,5884	0,6667	0,6667

Tabla 9 ENPS del juego de la transición energética en su variante con producción simétrica y mercado vigilado - estrategias optimas más probables de los agentes en el equilibrio en estrategias mixtas.

- El gobierno en los dos perfiles estratégicos presenta una estrategia pura en donde la probabilidad de optar por PPR es de un 100% lo cual es consistente con su carácter de dictador benevolente.
- Es importante resaltar que los perfiles estratégicos 1 y 2 para el caso de las empresas solo representan una parte del espacio de decisión de las mismas, como bien se señala en la Tabla 11 solo son perfiles estratégicos con mayores probabilidades por lo tanto su ocurrencia no resulta ser definitiva. En esta variante el equilibrio en estrategias mixtas da muestras de incertidumbre, por lo tanto, los pagos que prevén las firmas al decidir no son fijos, sino que se perfilan como esperados dependiendo de sus elecciones de portafolio y de las elecciones de su competidora.
- El equilibrio global en estrategias mixtas lleva a que el vector de pagos este determinado por el valor esperado del pago total de cada agente, por lo tanto,

en este caso se cuenta con un vector de pagos esperados E(b)= (2919.24, 1459.62, 1459.62)

- En esta variante las empresas tienen incertidumbre respecto a la transición efectiva de su competidora hacia la producción de Q_r, por lo tanto, el panorama de decisión no resulta ser tan claro estratégicamente hablando, en especial porque la vigilancia del gobierno y la estructura simétrica reducen el potencial de maximizaciones puras en términos competitivos.

5 Discusión de resultados

La intervención gubernamental genera cambios en el mercado en la medida en que se logra influir en las decisiones de los agentes por medio de incentivos económicos. El análisis de la interacción gobierno-empresa desde la teoría de juegos alimenta el cometido de entender cómo las políticas públicas pueden impulsar la transición cuando el gobierno es el agente conductor. Las modelaciones discretas propuestas en este trabajo y sus resultados permiten vislumbrar un enfoque preventivo para la política.

De manera general, los resultados evidencian que es importante considerar el tamaño de las empresas del sector energético y también el nivel de vigilancia institucional que se ejerce para evitar situaciones de desequilibrio en el mercado. Los dos factores mencionados pueden hacer la diferencia respecto a los resultados y el nivel de bienestar logrado después de aplicar una política pública.

En el juego de la transición energética el gobierno, en su papel de dictador benevolente, opta por una PPR como estrategia pura dado que al final esto conduce a niveles de bienestar mayores para las empresas del sector. A su vez, si el gobierno tiene la transición energética como prioritaria dentro de su agenda, este tipo de política resulta ser mucho más consecuente, en especial porque la transición energética requiere también una transición en términos tecnológicos. En tal caso, los subsidios se convierten en una herramienta importante para disminuir costos de adopción tecnológica.

Es importante mencionar que la transición no debe generar traumatismos fiscales. En ese sentido, iniciar con un impuesto al consumo y luego proceder con un subsidio financiado es un mecanismo mucho más prudente de actuación que además genera desincentivos para consumir energía producida con fuentes fósiles. Si se logra que el precio percibido de la energía renovable sea mucho menor a partir de subsidios y que el precio pagado a los productores sea mayor al que se perciben por energía generada con fósiles, la transición tendrá una señal de inicio ante el incremento de la demanda de este tipo de energía.

Por otro lado, la estrategia pura del gobierno de optar por una PPR muestra que las medidas de coerción a través de impuestos sin redistribución no resultan ser compatibles con un gobierno que busca maximizar el bienestar social. A su vez, la PPNR no genera incentivos suficientes para la transición energética, por el contrario, se disminuye la demanda y el acceso al servicio ante el aumento del precio; esto deteriora los beneficios de las firmas generando una perdida irrecuperable de eficiencia (Nicholson

& Snyder, 2015). Así mismo, al conocerse previamente que no habrá redistribución, las empresas no tienen ningún incentivo para pasar a una tercera etapa de transición.

La estrategia PPR del gobierno muestra la acción del gobierno como "agente conductor." Lo que más llama la atención de la revisión de escenarios discretos para el modelo base de Suarez y Gibaja (2019) son las diferentes reacciones de las firmas de acuerdo a su capacidad de producción y al nivel de vigilancia que se ejerce en el mercado. A continuación se exponen algunas de las implicaciones de los ENPS hallados:

Empresas con producción asimétrica y mercado vigilado. Versión principal del juego en la cual las empresas no cuentan con igual capacidad de producción. El equilibrio resultante de esta versión discreta que se describe en la Tabla 4 es Max, Min y Max, Min, a su vez su vector de pagos es b= (3260,1920,1340) lo cual implica que en el transcurso del juego la empresa con producción menor (e_2) aun comportándose competitivamente tenderá a subordinarse a la empresa (e_1) prefiriendo producir cantidades "Min" antes que cantidades "Max" en especial porque al optar por la segunda opción corre el riesgo de ver disminuidos sus beneficios finales, a su vez considerado que el equilibrio de Nash es un equilibrio competitivo e_1 descartará producir cantidades "Min" ya que puede producir por encima de tales límites y además frente a un equilibrio cooperativo Min-Min preferirá un equilibrio de Nash no cooperativo en donde puede percibir beneficios mayores en un escenario en donde produce Max esperando que su competidora produzca Min, este comportamiento aplica tanto para la etapa 2 como 3 aunque se asume que la subordinación se refuerza en la etapa 3 dado que al momento en que e_1 produce en el segundo Cournot ya cuenta con la información pasada de la etapa 2.

La ventaja de este escenario de equilibrio es que dada la vigilancia los incentivos para generar escenarios de desequilibrio no son atractivos para las firmas por lo tanto se garantiza que O=Q y por lo tanto existirá estabilidad de precios y en el caso de la etapa 3 las cargas del subsidio estarán equilibradas y por lo tanto los consumidores percibirán un precio menor para Q_r y las firmas percibirán precios mayores al producir energía con fuentes renovables.

La transición energética en este modelo inicial transcurre de manera exitosa, sin embargo la dinámica de subordinación podría llevar a que en términos aplicados la empresa más grande tarde más en pasar la totalidad de su producción a Q_r mientras la empresa pequeña emprende con mayor rapidez su transición, esto partiendo del hecho de que el efecto adicional del subsidio será mayor para la empresa de menor tamaño (e_2) y será comparativamente menor para la empresa más grande (e_1) a pesar de tener pagos mayores. Esto dado que las inversiones necesarias en tecnología serán dispares y por lo tanto se esperaría que e_1 conserve por más tiempo una porción de su capacidad de producción en Q_f mientras e_2 se transforma con mayor rapidez a producción con energía de fuentes renovables, no obstante dada su mayor capacidad e_1 buscará seguir siendo dominante en la etapa 3 buscando captar el mayor beneficio del subsidio de tal forma que pueda compensar sus costos de transición, e_2 seguirá optando por Min dado que a pesar de que se transición es más rápida seguirá teniendo capacidad menor a la de e_1 y la posibilidad de forzarse y producir Max involucra

percibir menores beneficios del subsidio al esperar que e_1 produzca Max lo cual resulta inconveniente en términos de compensar sus costos de transición.

Comparativamente los pagos percibidos en esta versión principal son menores a los percibidos en la variante con producción simétrica y mercado no vigilado, sin embargo, dada la imposibilidad de generar escasez en este modelo principal los pagos percibidos son los más favorables hablando en términos competitivos.

Empresas con producción simétrica y mercado no vigilado: En esta variante las empresas cuentan con una capacidad de producción igual en sus momentos Max-Max y Min-Min, además se asume que el mercado no está vigilado, por lo tanto, es posible generar desequilibrio que dé lugar a un aumento de precios dado un escenario en donde O<Q. . El equilibrio resultante de esta versión discreta que se describe en la Tabla 8 es Min, Min y Min, Min, a su vez su vector de pagos es b= (4110,2055,2055) lo cual implica que:

En términos meramente competitivos este es el escenario más favorable para las firmas dado que pueden percibir beneficios adicionales tanto en la etapa 2 como en la etapa 3 al producir cantidades mínimas que lleven al mercado a un estado de escasez en donde los precios pagados por los consumidores sean mayores, a su vez al momento del subsidio esto también permite que se distorsione la carga del mismo dando lugar a que la disminución percibida por el consumidor sea menor tal y como se aprecia en la Tabla 6.

En esta versión del juego dado que las dos firmas producen simétricamente, los escenarios de equilibrio Max-Min y Min-Max son menos atractivos en términos de sus beneficios potenciales dado que existe el escenario Min-Min en donde se produce por debajo de Q y pueden percibirse precios mayores, dado que las firmas a pesar de decidir simultáneamente conocen las condiciones del mercado saben que reducir la oferta tendrá como resultado mayor beneficio, por lo tanto Min-Min en este caso no se considera un equilibrio cooperativo, por el contrario es un equilibrio de Nash dado que optar por este perfil estratégico conduce a maximizar el beneficio individual, a su vez este equilibrio es sub-optimo socialmente en especial porque afecta de manera significativa al consumidor.

Los consumidores van a tener que pagar más por cada unidad de energía por lo tanto sus excedentes van a ser menores teniendo en cuenta que la diferencia entre su precio de reserva y el precio pagado se hará menor, de hecho, las fluctuaciones de precios al alza pueden motivar fácilmente la generación de mercado negro tanto en la etapa 2 como en la etapa 3 ante la existencia de demanda energética insatisfecha, en el caso de la etapa 3 en el espacio de equilibrio el hecho de producir Min-Min lleva a que P_r^3 percibido por el consumidor sea de 49 u.m lo cual da lugar a que las producciones Mínimas en la etapa de transición estén relacionadas con transiciones incompletas o bien con un mercado con un alto potencial de transacciones informales.

Esta variante del juego de la transición energética es la versión menos favorable en términos de bienestar general, de hecho, en un mercado no vigilado incrementar los valores de subsidio e impuesto puede traer amplias perdidas y choques negativos para los consumidores, en el mediano plazo las problemáticas generadas por el desequilibrio del mercado pueden decantar en costos adicionales al estado derivados del combate contra la clandestinidad, degeneración de la calidad del servicio, e importantes

limitaciones al acceso; la medida se perfila poco sostenible a través del tiempo e incluso podría dar lugar a que exista un retroceso y la transición se detenga para retornar a un modelo con energías producidas con fuentes fósiles.

Empresas con producción simétrica y mercado vigilado. En esta última variante, las empresas son simétricas y el mercado está vigilado se presenta un ENPS es estrategias mixtas que da cuenta de la existencia de incertidumbre y en donde las firmas tienen portafolios de estrategias puras con cierto nivel de probabilidad ante lo cual los pagos no son esperados con exactitud como en las variantes anteriores, en este caso las firmas buscan maximizar sus pagos esperado y además a pesar el potencial de escenarios es mucho más amplio dando lugar a que los equilibrios mostrados en la Tabla 11 sean probables pero no absolutos, en términos generales el vector de pagos esperados por los agentes es E(b) = (2919.24, 1459.62, 1459.62), las implicaciones para esta variante son las siguientes:

El hecho de que las empresas sean simétricas y el mercado este estrictamente vigilado da lugar a que la posibilidad de maximizar beneficios en estrategias puras se complejice especialmente porque las decisiones tomadas considerando la producción del competidor no son claras dado que no hay diferencias en tamaño por lo tanto hay mayor incertidumbre respecto a las acciones potenciales en la elección simultanea de las firmas al punto de que en el análisis racional de su competidora la firma que decide no asume como absoluto una decisión de la otra sino que le asigna una probabilidad respecto a su portafolio de decisiones.

La incertidumbre inmersa en el juego lleva a que la dinámica de transición que se da en desde la etapa 2 a la 3 también cuente con tal característica, por lo tanto, en términos prácticos una estrategia mixta implicaría una transición parcial, es decir, ante la incertidumbre de las firmas respecto al cambio de su competidora contarán con cierto grado de aversión al riesgo por lo tanto tenderán a las mezclas en sus planes de producción, por lo tanto existirá un espacio intermedio en donde convivirán tanto las tecnologías para producir energías con fuentes fósiles, como nuevas tecnologías para la producción con fuentes renovables, así las cosas, la transición será progresiva y en un inicio no será total, no obstante, en este caso este estadio intermedio no va en detrimento del bienestar de los consumidores ya que dentro de las posibilidades de decisión de las firmas solo existirán combinaciones en donde solo es posible el equilibrio o la sobre-oferta.

Esta versión del juego de la transición energética es la que más se asemeja a lo que ocurriría potencialmente en un entorno real en donde se motiva la transición y existe estabilidad institucional, las firmas no optarán por hacer su conversión total e inmediata, sino que lo harán pensando en sus beneficios futuros sin conocer exactamente el desenlace de los pagos, en medio de esto la oferta de energía con fuentes renovables ira en ascenso mientras se logra una transición tecnológica completa, y además se logra generar mayor confianza e incentivos para que las firmas continúen en su senda de transición.

Al analizar las variantes del juego de la transición energética es posible apreciar que la política pública redistributiva debe pensarse desde las condiciones y características particulares del mercado energético, uno de los aspectos más importantes recae en el nivel de vigilancia y regulación de los mercados de energía, si la institucionali-

dad es débil y hay poca capacidad regulatoria el escenario más probable es el de la variante de mercado no vigilado en donde se afecta negativamente a los consumidores y emergen costos potenciales ante el riesgo de generación de mercado negro y limitaciones al acceso que ponen en riesgo la sostenibilidad de la transición, en este caso sería preciso primero generar los mecanismos de vigilancia necesarios desde el gobierno antes de implementar cualquier tipo de intervención, sin fortaleza institucional las medidas tradicionales para impulsar la transición pueden generar más costos que beneficios y pueden inclusive llevar al fracaso del proceso.

Por otro lado, si existe fortaleza institucional y vigilancia suficiente es importante tener en cuenta la composición y tamaño del mercado de tal forma que se puedan generar incentivos proporcionales y transiciones tecnológicas efectivas y sostenibles en el tiempo por parte de las firmas, en el caso de las empresas asimétricas será necesario generar políticas transversales que mantengan a la empresa de mayor tamaño dentro de la transición y le permitan hacer atractiva su inversión a largo plazo, en este sentido la prolongación del subsidio en el tiempo es fundamental en el horizonte futuro de la transición, en especial porque debe asegurarse que a lo largo del tiempo el sector de generación renovable se haga atractivo para inversores privados, esta situación contrasta con el caso final de empresas simétricas y mercado vigilado en donde es claro que es necesario seguir aunando acciones para la consolidación de la transición especialmente sabiendo que la producción fósil no desaparecerá en las etapas iniciales, es necesario por tanto generar políticas adicionales que continúen aumentado los incentivos tanto para los consumidores como para los productores y favorecer especialmente la desinversión en el negocio de producción de energía con fuentes no renovables, trasladándolo a empresas que aceleren su ritmo de conversión tecnológica y productiva, además de complementarlo con políticas que motiven las interacciones con la academia, y la sociedad civil.

6 Conclusiones

La transición energética es uno de los retos contemporáneos más importantes y urgentes que afronta la humanidad. Dentro de ella, los gobiernos juegan un papel fundamental para un proceso de transición exitoso en el largo plazo. Sin embargo, la política pública debe pensarse considerando los rasgos particulares y riesgos potenciales ante su aplicación; en este caso la versión discreta, aquí propuesta, del juego de Suarez y Gibaja (2019) da cuenta de que el nivel de regulación inicial del mercado energético y su estructura de producción son aspectos fundamentales a considerar antes de aplicar medidas como impuestos o subsidios.

En concordancia a lo anterior, la fortaleza de las instituciones ligadas al sector energético es un factor importante si no se quiere generar una transición lesiva con el bienestar. Además, las características del mercado son fundamentales para prever el comportamiento de las firmas dentro de la transición. Esto última traza la hoja de ruta para políticas complementarias que aumenten la gradualidad de la transición, que no se perfila como un cambio instantáneo sino progresivo en donde la generación de

confianza y la preservación de los estímulos en el tiempo son relevantes para pensar en una transición conducida desde el gobierno.

La relevancia de los elementos antes mencionados da pie para demarcar que la transición energética tiene referentes a nivel internacional. Sin embargo, al no aber una receta exitosa ya probada, es necesario que cada país que la emprenda revise de manera cuidadosa su contexto de mercado energético y capacidades institucionales antes de tomar cualquier medida, el enfoque aquí presentado da pie para pensar de forma intuitiva en esos aspectos generales que deberían ser tenidos en cuenta previamente, de tal forma que se eviten distorsiones y se logren transiciones sostenibles en el tiempo que conduzcan a economías menos contaminantes.

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Transparência governamental em tempos de pandemia do COVID-19

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Abstract. Este estudo é sobre transparência de dados públicos em tempos de pandemia mundial Coronavírus Covid-19. Foi utilizada a combinação de dois eixos e de palavras-chave para selecionar os artigos publicados em 2020 nas bases de conhecimento ligada a Engenharia de produção. Devido ao curto período pesquisado houve um número pequeno de artigos selecionados, contudo os mesmos demostram que o tema já desperta a atenção de pesquisadores. A informação pública de qualidade possui duas funções determinantes: a de manter o cidadão conectado com os fatos e de combater a onda de fake news. O resultado da pesquisa propõem que no Brasil, Índia e Filipinas, há a falta de uma coordenação central de informações ocasionando desconfiança por parte da cidade e da mídia. Foi possível a identificação de dois modelos de avaliação, o primeiro oferecido pela Organização mundial da saúde (OMS) e o segundo pela OPEN KNOWLEDGE BRASIL (OKBR). Em comum foi identificado o tema granularidade.

Keywords: Transparência, Governo, Acesso a informação.

1 Introdução

A transparência de dados públicos, já vinha ganhando protagonismo na última década. Muito se deve a legislação e a cobrança dos órgãos de controle externo; também deve-se ressaltar a sociedade civil organizada. Com o advento da pandemia do Coronavírus Covid-19, diversas entidades passaram a fazer novas exigências sobre dados referentes a própria doença ou sobre informações de como está ocorrendo o enfrentamento a mesma.

A internet é um campo vasto e recheado de informações provenientes de fontes confiáveis e de sites com intensões duvidosas.

Os estudos apresentados estão sediados em dados de países como o Brasil, Filipinas e Índia. Demonstrando que o tema escolhido é de alta prioridade pois envolve a preservação de vidas humanas, a gestão de recursos públicos e a produção de informações confiáveis que combatem as fake news.

O problema a ser explorado é voltado a como e quais são as formas de estudo que estão sendo conduzidos, quais as dificuldades encontradas e se há perspectiva de pesquisas futuras.

Devido ao curto espaço de tempo encontrado entre o início da pandemia e o período em que a pesquisa foi realizada, pretende-se encontrar artigos que estejam ligados ao tema pandemia e dados abertos de governo.

2 Referencial teórico

O referencial teórico é a primeira atividade que um pesquisador deve realizar para que possa redefinir e responder a pergunta de pesquisa. Uma contribuição de valor que gera resultados deve ser fundamentada em varredura horizontal tão ampla quanto possível [1].

Os dados abertos do governo são norteados pela Open Government Partnership(OGP), essa organização padroniza a melhoria na prestação de serviços públicos integrando iniciativas sobre (1) acesso à informação, (2) participação cívica, (3) contabilidade pública e (4) alavancagem de tecnologia para fortalecer a governança [2].

A transparência nos dados de governo em relação do COVID-19, pode ser oferecida em formato de boletim diário ou de relatório [3], exportação de informações em arquivos com formato não proprietário [2] e em site do próprio governo [4].

As grandes redes sociais como Facebook, Twitter, YouTube, Reddit, Instagram, e Pinterest possuem uma forma padrão de enviar o retorno de notícias sobre o COVID-19 para os usuários. Priorizar fontes oficiais e tradicionais em detrimento dos meios de comunicação como uma maneira de controlar o “infodemia”[5].

O acesso a informação de qualidade afeta a coerência na tomada de decisões de governantes e de empresários e requer uma boa governança de dados. A fim de serem reutilizados para o geração de valor social e econômico [2].

Concorrem com os sites governamentais o acesso facilitado as mídias sociais, que são barulhentas e podem apresentar inconsistências quantos aos dados apresentados.

Nesse momento onde o isolamento social é uma das formas de conter a velocidade de expansão do vírus, as pesquisas estão sendo direcionadas para os dados oferecidos em sites governamentais federais, estaduais ou municipais.

Enquanto a informação das formas de combate e prevenção a disseminação do vírus são pilares dos governos, ocorre o compartilhamento de falsas notícias como ocorreu no Irã onde se aconselhava o uso de uísque e mel para a cura [5]. Lembrando que esse país possui rígido controle sobre o consumo de bebidas.

Os modelos de divulgação de dados apresentado pela OKBR [4] e pela OMS [3], partem de dados provenientes de sistemas voltados ao accountability [5], [4], [3] e [2].

Porém alguns dados são tratados para assegurar a privacidade dos cidadãos, assim os mesmos não passariam por discriminação; esse tratamento também é realizado com os dados dos portadores de HIV.

Devido a pandemia, diversas fragilidades na captação de informações, falta de centralização e processamento de dados, gestão de recursos humanos e organizacionais ficaram expostos [2].

3 Metodologia

Este trabalho possui base qualitativa sendo nele aplicado uma revisão sistemática de literatura voltada para a seleção de artigos. O portal de periódicos CAPES [6], dispõem de ferramenta que filtra bases do conhecimento, demonstrando na Fig. 1 possibilidade de pesquisa em 51 bases das quais foram selecionadas somente as que oferecem artigos.

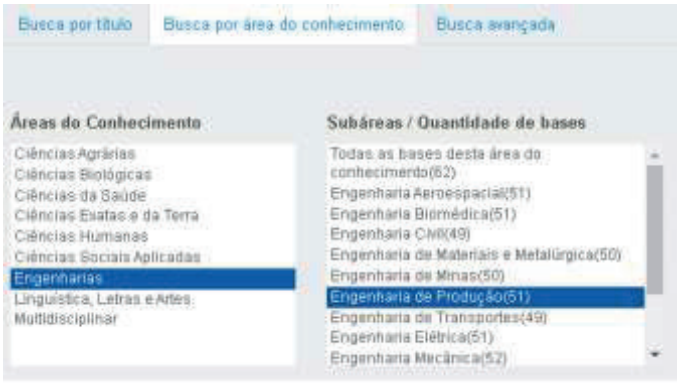

Fig. 1. Busca pela subárea do conhecimento Engenharia de Produção no portal CAPES.

Segundo [7], que nos apresenta uma técnica da revisão sistemática de literatura que em suas primeiras fases determina a seleção de palavras chave. Foi realizada a seleção das palavras chave para obter artigos que estivessem ligados a temática do eixo 1-Pandemia ("coronavirus" or "covid-19" or "pandemic" or "SARS") e do eixo 2-Dados abertos ("transparency" or "open data" or "open government data" or "accountability").

A Table 1 apresenta as bases selecionadas e o resultado obtido com o emprego do comando na pesquisa avançada disponível em cada periódico.

Table 1. Bases selecionadas para pesquisa.

Nome da base	Tipo de informação	Resultados
SciELO.ORG	Textos completos, Sites com periódicos de acesso gratuito	11
CrossRef Search *	Referenciais com resumos	-
Elektronische Zeitschriftenbibliothek (EZB) = Electronic Journals Library	Sites com periódicos de acesso gratuito	0
WorldCat	Referenciais com resumos	0
E-Print Network: Research Communications for Scientists and Engineers	Arquivos Abertos e Redes de e-prints	23

Hyper Article en Ligne: HAL	Arquivos Abertos e Redes de e-prints	9
International Network for the Availability of Scientific Publications: INASP *	Sites com periódicos de acesso gratuito	-
OAIster	Arquivos Abertos e Redes de e-prints	0
Japan Science and Technology Information Aggregator Electronic: J-STAGE	Referenciais com resumos	0
Google Scholar	Ferramenta de Busca	7
Directory of Open Access Repositories: OpenDOAR	Arquivos Abertos e Redes de e-prints, Repositórios Institucionais	0
Directory of Open Access Journals - DOAJ	Sites com periódicos de acesso gratuito	0
SciELO Cuba - Scientific Electronic Library Online	Textos completos, Sites com periódicos de acesso gratuito	0
Latindex: Portal de Portales	Textos completos	0
ROAD Directory of Open Access scholarly Resources	Referenciais com resumos	0
Latindex : Sistema Regional de Información en Línea para Revistas Científicas de América Latina,	Referenciais com resumos	0
Latin American Open Archives Portal: LAOAP *	Arquivos Abertos e Redes de e-prints	-
Open Access and Scholarly Information System: OASIS.BR	Sites com periódicos de acesso gratuito	4
re3data.org	Ferramenta de Busca, Repositórios Institucionais	0

As bases que possuem asterisco ao final de suas descrições não foram utilizadas por não possibilitar consulta via comando ou por não oferecer seleção por intervalo de ano.

Durante a execução da pesquisa foi aplicado o filtro de data indicando o ano das publicações que possuíssem somente ano igual a 2020. Em relação ao idioma não foi aplicado nenhuma restrição.

Foram encontrados 12 artigos no total, como pode ser observado na Table 2 a maioria dos periódicos não retornou nenhum resultado.

Table 3. Artigos selecionados

Autor(es)	Ano	Revista	Objetivo	Resultados
[8]	2020	Gestão e Sociedade	…promover reflexões sobre questões já evidentes em torno de como a transparência governamental, na atual conjuntura, tem se desenvolvido.	Futuros estudos, reflexões e analises podem sugerir uma agenda de estudos que investiguem se o aumento da transparência

				nos governos é causado pelo acentuamento da crise.
[4]	2020	Gestão e Sociedade	Analisar a construção da transparência sobre a Covid-19 pelos estados brasileiros.	Os avanços detectados neste curto e tenso período de tempo. As respostas estão sendo positivas.
[9]	2020	Cadernos de saúde pública	Quais modelos de comunicação devem embasar a narrativa oficial para criar as condições de colaboração e parceria com a mídia?	Enormes obstáculos aparecem combinados com o vácuo de informações oficiais. Cabe ao governo valer-se de sua ampla visibilidade para produzir informações seguras em seus sites.
[2]	2020	SSRN Electronic Journal	Investigar o estado dos dados abertos do governo nas Filipinas e compara o acesso a informações de saúde durante a pandemia COVID-19.	Ele tira as lições da criação do hub de dados de saúde relacionados à pandemia e o modela como uma forma de compartilhar dados mais sistemáticos no futuro.
[3]	2020	medRxiv	Responder duas perguntas, primeiro, quais são os dados mínimos que o público precisa saber para compreender a gravidade da situação e cooperar com o governo? Em segundo lugar, quão diferente é a qualidade dos relatórios de dados de um estado para outro?	Após o desenvolvendo uma estrutura sistemática para avaliar a qualidade dos relatórios de dados CO VID-19, em seguida, foi avaliada a qualidade dos relatórios feitos pelos estados da Índia. Com base nessa estrutura, forneceu-se um modelo mínimo que os estados podem usar para relatórios diários de dados COVID-19.

A Table 1, demonsta os artigos selecionados após a coleta de suas versões em arquivo .PDF, tradução em alguns casos e seu fichamento.

4 Apresentação dos resultados

Os resultados obtidos com a pesquisa horizontal apresentam uma forma de cobrança sobre a qualidade dos dados apresentados em sites governamentais.

Os modelos de avaliação são baseados na OMS, no freedom of information (FOI), OPEN KNOWLEDGE BRASIL (OKBR) dentre as 5 fontes bibliográficas encontradas.

A preocupação com a centralização dos dados e com a privacidade dos cidadãos é recorrente em [3] e [2].

A forma de acesso e a facilidade de interpretação devem ser priorizadas frente aos termos médicos e técnicos envolvidos na apresentação dos dados.

Colabora [3], com essa afirmação pois a Índia necessita de padronização dos dados apresentados, para que atraso, disparidade de informação divulgada entre os estados e o governo federal parem de causar desconfiança.

No Brasil a divulgação de dados vem sendo avaliada com base no padrão da OKBR, que é segmentada em: Conteúdo, Granularidade e Formato.

A verificação de dados e informações disseminados em redes virtuais, WhatsApp, Twitter, Instagram, entre outros é extremamente veloz frente a produção de dados oficiais [5].Ocasionando uma guerra de narrativas, sensacionalismo, senso comum, que geralmente tem cunho político e tendem a desinformação do cidadão leigo.

O modelo de avaliação aplicado pela OKBR, prioriza dados relacionados com a doença e como esses dados podem ser exportados para avaliação de terceiros.

Dimensão	Critério	Descrição	Pontuação
Conteúdo	Idade ou Faixa Etária	Idade ou faixa etária das pessoas que pertencem ao grupo de, no mínimo, casos confirmados	0 = não apresenta; 0,5 = apresenta apenas uma média geral; 1 = apresenta idade ou faixa etária.
	Sexo	Sexo das pessoas que pertencem ao grupo de, no mínimo, casos confirmados	0 = não apresenta; 0,5 = apresenta uma média geral; 1 = apresenta idade ou faixa etária.
	Status de atendimento	Especifica casos hospitalizados (internação e UTI) ou em isolamento domiciliar	0 = não apresenta; 1 = apresenta.
	Doenças preexistentes	Presença de doenças preexistentes/ comorbidades (diabetes, hipertensão etc.)	0 = não apresenta; 0,5 = apresenta em algum grupo (ex. óbitos) 1 = apresenta para todos os casos
	Ocupação de leitos	Quantidade de leitos ocupados no estado em relação ao total disponível.	0 = não apresenta; 1 = apresenta.
	Outras doenças respiratórias	Número de casos de Síndrome Respiratória Aguda Grave registrados ou outras condições que possam indicar Covid-19	0 = não apresenta; 1 = apresenta.
	Testes disponíveis	Quantidade de testes de que o estado dispõe	0 = não apresenta; 1 = apresenta.
	Testes aplicados	Quantidade de testes já realizados. A quantidade de casos descartados, que pode ser somada à de confirmados, pontua neste tópico, desde que indicado que foram descartados por critério laboratorial	0 = não apresenta; 1 = apresenta.
Granularidade	Microdado	Cada caso é um registro	0 = não apresenta; 0,5 = apresenta de um grupo de casos; 1 = apresenta.

	Localização	Nível de agregação geográfica dos casos divulgados	estado = 0;
			cidade = 0,5;
			bairro, distrito ou hospital =1

Formato	Visualização	Painel para consulta do público em geral	0 = não apresenta; 1 = apresenta.
	Formato aberto	Dados estruturados em ao menos uma planilha em formato editável, de preferência aberto (CSV, ODS)	0 = não apresenta; 1 = apresenta.
	Série histórica	Uma base de dados única e atualizada contém o histórico completo, desde o início do registro de casos	0 = não apresenta série; 0,5 = série em gráfico; 1 = série em uma base completa.

Fig. 2. Modelo de avaliação aplicado pela OKBR. Fonte:[4] .

Enquanto o modelo de avaliação aplicado pela OMS, prioriza a Acessibilidade e Granularidade.

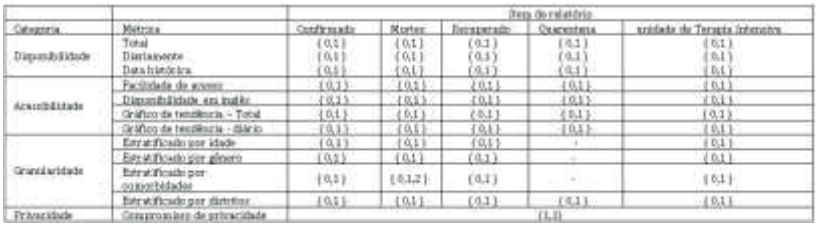

Fig. 3. Modelo de avaliação aplicado pela OMS. Fonte: Traduzido de [3]

Dentre os modelos da OMS disposto na **Fig. 2Fig. 1** e da OKBR apresentado na **Fig. 3**, observa-se que ambos possuem em comum o item Granularidade.

Como pode ser visto o tema Pandemia e Dados abertos do governo vão render diversas pesquisas, tanto voltadas para a administração de recursos financeiros, orçamentários, quanto para humanos e de saúde.

Dentro da literatura disponível não foi encontrado paralelo em outras pesquisas similares, desta forma o estudo oferece também um foco de pesquisa voltado para o combate a desinformação.

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Current problems to achieve interoperability, influenced by the process domains, difficulties and challenges for the logistics area in its horizontal and vertical integration

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Abstract. The quest to overcome monetary challenges, competitiveness, customer demands, technological adaptation and innovation, are daily icons in the routine of the manufacturing industry, especially in this era of Industry 4.0. When dealing with logistical flows, the process becomes more complex. The amount of heterogeneous data shared, together with the diversity of domains involved in the flow, make horizontal integration in this flow more and more important. This structure concentrates and translates information in order to make the decision-making process, forecasting demands for input purchases, forecasting deliveries for customer sales much more accurate, increasing the process maturity level, thus contributing to its competitiveness in the inserted scenario. In this way, it is essential that the meaning assigned to each information is unequivocally shared. This work aims to understand the current issues involved in horizontal and vertical integration, together with knowledge related to semantic interoperability, logistical flows, decision making, demand forecasting, industry 4.0 and multiple domains. This research showed through the formalization of information and knowledge obtained about logistical flows and their routines, that even with adversities in transport, market instabilities / seasonality, it is possible to obtain greater control under the flow chain of purchase of inputs until delivery to the market customer, integrating it obtaining better forecasts, ensuring delivery time and product quality, and consequently, respecting cost, processing, quality, delivery requirements with greater precision and reliability.

Keywords: Manufacturing Systems, Semantic Interoperability, Decision-Making Support, Supply Chain, Blockchain, Horizontal Integration.

1 Introduction

The search for competitiveness and performance, brought the need to seek new ways to innovate. From this gap, the use of concepts and methodologies from Industry 4.0 were increasingly applied to structure a competitiveness strategy, development of processes and people, maturity gain, for example.

Industry 4.0 brought with it technological advances in terms of Internet of things, machine learning, connectivity, procedural independence in all existing areas: health, psychological, metallurgical, etc. As pillars of support, Industry 4.0 is based on 9

pillars: Robotics, Simulation, Systems Integration, Industrial Internet, Cyber Security, Cloud, Additive Manufacturing, Augmented Reality and Big Data and Analytics.

Its objective is to establish faster, more flexible and efficient processes, thus promoting the representation / integration of physical resources with digital ones, connecting machines, systems and real assets in order to produce items with higher quality, more profitable, lower production cost, resulting in a most performing process, consequently increasing maturity, speed in more assertive decision making and competitiveness [11][12][17].

Cultural and paradigm change has become the first barrier to be overcome for its implementation. When dealing specifically with the application perimeter in terms of the logistics of a manufacture, we can explore the theme and map its difficulties, opportunities and challenges [17].

This article provides a contribution to industrial logistics, pointing out the difficulties, challenges and problems encountered by logistics related to the lack of semantic interoperability between platforms, the absence of integration between systems, companies, suppliers and customers in the production systems when different types of parts, companies, people, production processes and sectors are involved. The main result is an overview of the existing gaps, allowing the discussion on the possibilities of dealing with the challenges faced by the complete supply chain: raw material purchase, transformation and customer sale.

This work will be structured as follows: session 2 shows the problem statement; section 3 presents the content involved; session 4 deals with the analysis of the discussion that involves the subject of this article and, finally, session 5 presents the conclusion of this research.

2 Problem Statement

Logistics in industrial companies have an important and challenging role. Its greatest difficulty is in knowing the quantity to be purchased of raw material and its delivery time to the customer. It is extremely important that the three main macro environments of logistics are clear: MRP (source), productive planning (Maker) and sales (delivery):

- **MRP (Source):** Responsible for all the planning of raw material purchase, strategy and transport costs until the raw material enters the factory, suppliers. Thus, we can highlight that its main task is planning the correct amount of raw material, without the correct deadline for not being responsible for production line stops, customer delays and increased transportation costs.
- **Productive Planning (Maker):** Responsible for planning the production of products, in the correct sequence, so as not to impact the cycle time of the line with many setups, without excess parts in order not to produce much more than the quantity sold, generating stock, according to the quantity of inputs purchased, and with flexibility of changes.
- **Sales (delivery):** Responsible for the beginning and end of the entire chain. It is through it that we receive customer input (request) or sale of products, and also that executes the delivery according to deadlines and quantities signed between company and customer.

So, the challenge is to buy the right quantity, with a time and cost of transport as planned, respecting the processing time and cost, the deadline and price agreed with the customer. In this way, we can see many challenges in its trajectory, taking into account the constant change of scenery, flexibility to adapt to new demands and cancellations. This process is explicit in Fig. 1, where it exposes the main sectors involved in the process and the requirements involved.

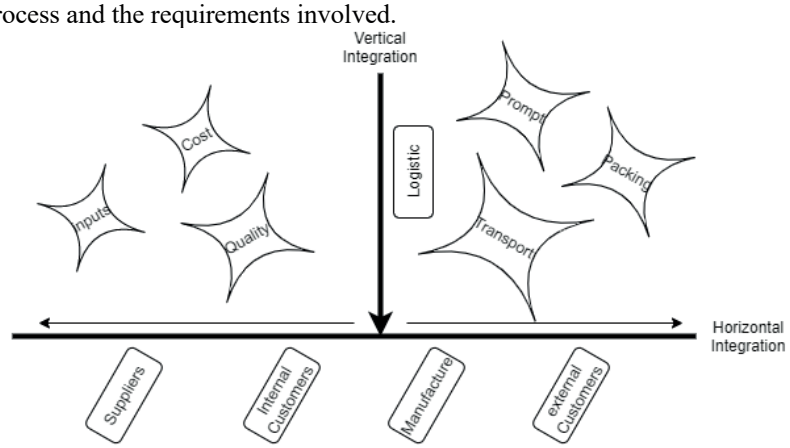

Fig 1. Logistic Environment, its influences, and information flow between sectors.

Figure 1 illustrates in its horizontal axis the need and importance of horizontal integration between sectors, so that communication occurs in a unique, centralized, interoperable way and indicates its main communication axes (suppliers, logistics, manufacturing, external customers, internal customers); in its single main axis called "Logistics" we can see the influence and importance of vertical integration under it, and the influences that are under pressure (raw material cost, taxes, transport cost, the correct delivery deadline...).

3 Current Issues

The current issues were researched and structured according to the main topics related to the research objective: I) Vertical and Horizontal integration; II) supply chain; III) smart factories.

3.1 Horizontal and Vertical Integration for the Logistics sector

The supply chain has a large extent in terms of communication between processes because it starts within the domain of the suppliers and ends with the delivery of the product to the customer. The flow of information generated, the changes along the entire logistical flow are large. Any change that has a big impact, since it is most often imported, many suppliers and customers are not located nationally, making this communication more distant and slow. Industry 4.0 has been collaborating with this problem over time, for its evolution, since it brought support tools, providing the integration of different sectors and companies, making the information homogeneous

to all interested parties, in this way we can name two types of integration: Horizontal and vertical.

The vertical and horizontal integration of production systems is directly linked to the concept of Advanced Manufacturing (Industry 4.0). This is because it aims to make the industry operate in a universal way, through a process of digital transformation. In this way, the production process starts to be optimized, reducing the moment when activities happen in the production chain.

- Vertical integration refers to the ability to integrate, reconfigure and make production processes more flexible, from product development to manufacturing. Among the advantages of vertical integration, we can mention the increased flexibility of the factory, increased reliability in production, reconfiguration of the production system, increased variety of products.
- Horizontal integration refers to the sharing of data and information between the different information systems, devices, and software that support the productive activity. In this way, the collection, processing, and analysis of data help to increase the precision and speed of decision making in the industry. This approach has a large volume of data and information that qualifies and improves the performance of the manufacturing environment. The main advantages of horizontal integration are agility in decision making, increased application of decision making through the integration and consistency of data and information, incorporation of intelligence and decision making in production systems, qualification of decision making based on systematic analysis of data in real-time [18].

In this way, the logistical flow becomes more agile for changing the scenario, type of transport used, mapping of alternative routes, roadblocks, and cargo tracking, for example.

3.2 Supply Chain

In today's competitive business environment, supply chain performance is one of the most critical issues in many industries. Because it is through it that the entire production flow is dependent, impacting productivity, product cost, added value, for example. For its performance control, measuring the performance of the supply chain is essential for efficient supply chain management. In the last two decades, several structures and systems have been developed to meet this need [1].

Supply chains are involved in the entire product life cycle, from the acquisition of materials to manufacturing and distribution, customer service, and, eventually, product recycling and disposal. Due to this fact, the need for all sectors and activities should be interconnected, occurring the interoperability of data and information are available to all.

Identify whether customer needs are met, understand business processes, make quick and accurate decisions, make progress possible, track progress, and identify bottlenecks, waste, problems, and opportunities for improvement.

To assist all this transit of information flow, which circulates along the three macro sectors of the supply chain (purchasing, production planning, and sales), we can insert technology from Industry 4.0, such as Blockchain.

Blockchain is a point-to-point distributed data infrastructure that allows for the creation of decentralized currencies (e.g. Bitcoin), self-executing digital contracts (smart contracts), and active smart contracts that can be controlled over the Internet (smart property). The technology uses a shared data infrastructure that updates in real-time and can process and settle transactions in minutes using computer algorithms, without the need for third party verification.

Integrated with other technologies, such as the Internet of Things (IoT), Blockchain can be used to create a permanent, shareable, actionable record of all moments of a product's journey through its supply chain, creating efficiencies in all the chain. Greater visibility facilitated through these technologies can also allow traceability, authenticity of the product, and legitimacy [16].

In this type of market, the definition of transport services must take into account not only the origin and destination of the elementary displacement but also the characteristics of transport resources. These characteristics must allow the transport of resources to easily identify products that can be loaded together to optimize the loading feature [6].

3.3 Smart Factories

A fourth industrial revolution is taking place today, structuring and innovating a future that will be heavily dependent on the acquisition and sharing of data in all sectors, including the supply chain. This vision of business, services, and interconnected sectors, processes, and information systems (SI) is only possible due to exceptional technological developments, especially in mobile devices. Mobility, or independence, is therefore one of the top priorities in the industrial supply chain. These developments are expected to provide a foundation for the virtual supply chain, with optimization, simulation, and decision support based on online operational data. In the Internet of Things (IoT) that the supply chain can become self-adaptive systems in which intelligent objects operate and deciding to learn autonomously [15] and execute, becoming more independent of human labor, making processes faster, optimizing the time and labor of everything and everyone involved.

Virtualization is a promising approach to deal with these challenges. Enables simulation and process optimization using systems software instead of performing physical experiments, thus being able to set up scenarios, simulate forecasts, analyzing virtually hypotheses with greater speed and agility. Consequently, supply chains can monitor, control, plan, track, and optimize remotely and in real-time using the Internet, based on virtual objects, rather than on-site observation [2].

4 Discussion

This research is working to highlight issues relevant to the knowledge requirements for semantic interoperability in the manufacturing and decision making system. These questions supported a proposed conceptual framework that aims to formalize this study, to justify its relevance to the topic addressed.

For this article, research was carried out with two groups, each group consisting of 3 people, of whom work with logistics, distributed among purchases, productive

planning, and sales. The groups were chosen because they have similar functions, are in the same company, and work with different products and manufacturing processes. The two groups were interviewed separately and at the same time by the authors of this work so that neither would interfere in the opinion of the other group. Routine issues were raised, which are the challenges, strengths, and weaknesses points and opportunities within the logistics sector in a macro way and each of the 3 sectors. Issues related to Industry 4.0 and its tools were also mentioned and presented, how technological innovation will impact and influence everyone soon.

After the interviews, all the content pointed out was discussed with the supervisor responsible for the sector. Thus, as a product of both groups, we can combine the following outputs, highlighting their main problems or difficulties:

- Decision support to strategic decision making according to forecast of prognose and sales;
- Existence of several systems bases for calculating inventory control;
- Need to create a definition regarding the minimum/maximum inventory per supplier and customer;
- Better optimization of the shipping time according to the quantity and type of cargo;
- Time optimization X Transport cost;
- Develop other local suppliers, so that they are not tied to international suppliers, often located outside the country;
- Correlate, understand and standardize the needs and visions of customers and suppliers;
- Level the production, to reduce the number of setups in the line, in the correct quantity and time, so that there is no over or missing produced parts;
- Develop a system that demonstrates the best sequence/scenario to be produced;
- Addresses the challenges of the person responsible for purchasing inputs so that they arrive in the correct quantity and time, with the transportation cost previously calculated;
- Likewise, address sales challenges, so that you can meet deadlines and prices agreed with the customer;
- Speed and interchangeability to adapt to changing market scenarios.

Based on the problems/work solutions used as basis for this work, Table 1 is proposed, which shows specific analysis by categorization, positioning each work according to its disciplines and degree of importance to the research. The classification criteria adopted were (Table 1):

1. Referring to works that address issues related to logistical interoperability problems:
   - (D1) Specific case: articles/books intended for the field of interoperability related to manufacturing.
   - (D2) Generalized case: articles/books not dealing with the field of interoperability.
2. The date of publication of the article:
   - (T1) Recent: articles/books published with date from 2014.

- (T2) Less recent: articles/books published until 2014.

3. About articles and books reporting cases and deals with specifically logistical interoperability:
   - (C1) Yes: refers to the literature of practical examples of difficulties encountered in logistics in manufacturing industries.
   - (C2) No: it refers to the literature that does not provide examples of difficulties encountered in logistics in manufacturing industries.

Table 1. Related works classification according to each research issue

Article	D1	D2	T1	T2	C1	C2
Barata, João; Rupino Da Cunha, Paulo; Stal, Janusz (2018)		X	X			X
Monostori, László; Valckenaers, Paul; Dolgui, Alexandre; Panetto, Hervé; Brdys, Mietek; Csáji, Balázs Csanád (2015)	X		X		X	
Balfaqih, Hasan; Nopiah, Zulkifli Mohd; Saibani, Nizaroyani; Al-Nory, Malak T. (2016)		X	X			X
Tsolakis, Naoum; Bechtsis, Dimitrios; Srai, Jagjit Singh (2019)		X	X		X	
Memon, Muhammad Ali; Karray, Mohamed Hedi; Letouzey, Agnès; Archimède, Bernard (2017)	X		X		X	
Tu, Mengru; Lim, Ming K.; Yang, Ming Fang (2018)	X		X		X	
Wang, Yingli; Han, Jeong Hugh; Beynon-Davies, Paul (2019)		X	X		X	
Pizzuti, Teresa; Mirabelli, Giovanni; Grasso, Giovanni; Paldino, Giulia (2017)	X		X			X
Madenas, Nikolaos; Tiwari, Ashutosh; Turner, Christopher J.; Peachey, Sophie (2015)	X		X		X	
Jamali, Gholamreza; Asl, Elham Karimi; Zolfani, Sarfaraz Hashemkhani; Šaparauskas, Jonas (2017)		X	X		X	
Madhwal, Yash; Panfilov, Peter B. (2017)	X		X		X	
Panetto, Hervé; Iung, Benoit; Ivanov, Dmitry; Weichhart, Georg; Wang, Xiaofan (2019)		X	X		X	
van Smeden, Maarten; de Groot, Joris AH; Nikolakopoulos, Stavros; Bertens, Loes CM; Moons, Karel GM; Reitsma, Johannes B. (2017)		X	X			X
Verdouw, C. N.; Wolfert, J.; Beulens, A. J.M; .Rialland, A. (2016)		X	X			X
Zdravkovic, M.; Panetto, H (2017)		X	X			X
Gómez, J.; Salazar, I.; Vargas, P. (2016)		X	X			X

It is observed in Table 1, that there are some unexplored flaws: in the works that deal with issues related to specific logistics problems, which bring cases, cyclical examples, difficulties encountered by the activity (C1), they were identified in only 56.25% of the articles selected, the which demonstrates, through the analyzed sample, that it is still a field to be explored. It can be noted that over the years, the theme has been growing and gaining more literature on it, with a notable increase from the year 2017. Where else can we observe certain literature reporting the application of interoperability (D1), which presented in this sample analyzed only 37.5% of the articles addressing the topic, for dealing with logistical problems, which shows a great field to be explored, even more, when we try to relate to the expansion of Industry 4.0, IoT, communication.

5 Conclusion

There are many challenges encountered by the logistics sector not only for the manufacturing industry but in its entirety. The fact that it encompasses a long path of responsibility that impacts the whole makes this perimeter even more complex and sensitive. There are many problems encountered due to the lack of interoperability and the amount of information and decision making that occur at all times, changes in political and governmental scenarios, cultures, distances, characteristics of types of transport are some of the challenges that make those responsible to quickly create scenarios and options to create solutions to problems that have occurred. Inside of Industry 4.0, many tools can be applied for a better degree of utilization, fluidity, reliability and speed, through the use of artificial intelligence, data interoperability, data collection and treatment, innovating it bringing time and cost benefits for the sector and the entire productive chain involved. Through the bibliographic analysis, we can observe that this theme is still little explored, taking into account the sample, because little more than half of the articles brought examples of logistical problems and so little about interoperability, communication networks, communication optimization, addressing issues of machine learning, artificial intelligence, for example. In this way, we highlight a vast field to be explored. As a suggestion for future work, to contribute to the improvement of these identified gaps, the application of ontological rules which will connect input items, monitoring and ensuring the output of products according to specifications. The application of artificial intelligence techniques to predict market scenarios, predict and provide paths according to changes in the global oscillation, transport crisis, lack of products at suppliers, better delivery routes based on transport cost, thus applying machine learning the system will be linked together, improving its interoperability and horizontal and vertical integration.

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Un modelo de medición de la calidad del servicio : Caso de una empresa de mantenimiento de motores

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Resumen. Se propone un modelo para medir la calidad de servicio de una empresa, donde el cliente del servicio es otra empresa. Para ello se definieron seis dimensiones que contiene la percepción del servicio, estas son: experiencia en el servicio, interacción con clientes, infraestructura y repuestos, capacidad técnica del personal, tiempos de entrega e imagen corporativa. Luego basado en el concepto de *desconfirmación* de Grönroos [2], se construye un modelo que se plasma en un índice de percepción, para luego aplicarlo a una empresa de mantenimiento de motores eléctricos. El resultado del índice de percepción de calidad de servicio es de un 86% de satisfacción de clientes en la organización donde se llevó a cabo el estudio. A través de este indicador se puede inferir cuáles son los puntos altos y deficientes en la gestión de calidad de servicio mediante el análisis de las distintas dimensiones que componen el modelo.
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Keywords: Calidad, Servicios, Modelo de medición, Motores.

1 Introducción

Los modelos de medición de la calidad de servicio representan en la actualidad un instrumento que permite a las organizaciones y empresas que ofrecen un servicio, medir la satisfacción de sus clientes con los servicios recibidos en función de ciertos factores y dimensiones propios de su naturaleza. Los modelos de medición de calidad de servicio más utilizados y de mayor aceptación corresponden al modelo *Service Quality* SERVQUAL [1], que se basa en la comparación de las expectativas versus la percepción del servicio recibido, al igual que el desarrollado por Grönroos [2] denominado modelo nórdico de calidad. Por otro lado, se encuentran los modelos cuya evaluación de la calidad se fundamentan sólo en la percepción del cliente al momento de recibir el servicio, como el modelo SERVPERF [3] y el modelo jerárquico multidimensional [4], cuyas posturas se sustentan en que no es necesario incluir las expectativas en la evaluación de la calidad del servicio, debido a que este factor se basa sólo en la percepción del resultado del servicio [5].

El modelo conceptual que se propone en este estudio, a diferencia de los modelos citados anteriormente, considera elementos propios de un servicio de tipo industrial en el cuál el cliente final no necesariamente es una persona, sino que corresponde a una organización o empresa. Debido a esto, las dimensiones que lo conforman son parte importante del proceso de producción y representan factores claves para darle una continuidad operacional al servicio. En la literatura revisada [1, 5], es posible afirmar que en la mayoría los casos, los modelos utilizados para medir la calidad de servicio son aplicados a personas como cliente final, no encontrándose ningún estudio en el cual el cliente final sea una organización o empresa, en este punto radica la diferencia esencial entre el modelo propuesto y los modelos de la literatura revisada.

En los puntos siguientes se presentará el modelo, su aplicación, resultados y conclusiones.

2 Desarrollo del modelo

El presente trabajo es del tipo cuantitativo, no experimental de corte transversal-descriptivo y busca generar un modelo que permita medir la percepción de la calidad del servicio prestado en una empresa. Para ello, se propusieron 5 etapas que se describen a continuación:

2.1. Definición de dimensiones; consiste en la definición de las dimensiones a evaluar y que serán parte integrante del modelo, para ello se consideran los componentes más críticos del servicio que se desea evaluar.

2.2. Generación del Modelo; desarrollo de un modelo con las relaciones de interdependencia y funcionalidad entre ellas. Para ello se consideró el modelo conceptual de Grönroos [2] que se basa en el paradigma de la "*desconfirmación*" el cual plantea que el nivel de calidad está dado por la diferencia entre la Expectativa del usuario (E) y lo Percibido (P) en el servicio por el usuario. Además, se consideró los modelos de Brady [5] y Lozada [6], que consideran las dimensiones sobre el cliente evalúa la calidad del servicio. En el modelo propuesto, el cliente evalúa cada dimensión por separado, esta valoración luego se pondera por el peso específico de cada una, peso que se determina mediante técnica de decisión AHP [7]. Finalmente, la suma de esas percepciones conduce a una evaluación global de la calidad del servicio.

2.3. Generación del instrumento de medición; generación del instrumento de evaluación (cuestionario) en base al modelo propuesto con una escala Likert de respuestas, el cual es aplicado a una muestra piloto en primera instancia.

2.4. Análisis de confiabilidad y validez; para verificar que el modelo de medición de calidad de servicio propuesto mide efectivamente lo que se desea medir, se realizan las siguientes pruebas estadísticas: Alpha de Cronbach [8]. y Análisis Factorial Exploratorio [9].

2.5. Evaluación de resultados; se establece el método para el cálculo del Índice de percepción de calidad de servicio, que será el indicador del nivel de la calidad de servicio, en función del cuestionario aplicado. Este indicador se expresa en el rango de 0 a 1. Luego se aplica el cuestionario definitivo a la muestra

total de clientes y finalmente se realiza un análisis de los resultados para determinar el nivel de servicio otorgado por la empresa en estudio.

3 Aplicación del modelo

La aplicación de las etapas descritas en el punto 2, se realizó a una empresa chilena de nombre Ferroman S.A., que se dedica a los servicios de asistencia técnica de motores eléctricos de media y alta tensión. En donde se seleccionaron 6 dimensiones que conformaran la base del modelo propuesto. En la Tabla Nº1, se presenta los factores y las dimensiones que las agrupa.

Tabla 1. Resumen de indicadores estadísticos

Factores	**Dimensión que los agrupa**
Años de presencia de la empresa en el mercado	Experiencia en el servicio
Experiencia en servicios	
Disposición a atender requerimientos de clientes	Interacción con clientes
Comunicación con clientes	
Infraestructura disponible	Infraestructura y repuestos
Ubicación geográfica	
Calidad de los insumos y repuestos	
Años de experiencia laboral del personal	Capacidad técnica del personal
Formación educacional del personal	
Plazos de entrega de equipos	Tiempos de entrega
Logística de transporte	
Reconocimiento de la marca en el mercado	Imagen corporativa
Certificaciones de la empresa	

Una vez obtenidos los factores y la dimensión que los agrupa, se estructura el modelo conceptual que se presenta en la Figura 2. Luego se desarrolló un cuestionario que consta con un total de 15 preguntas dividido en 6 dimensiones. El cual se validó, ya que tiene un nivel de confiabilidad y consistencia interna aceptable de acuerdo al Alpha de Cronbach obtenido, y que el modelo se ajusta a un Análisis Factorial Exploratorio. En la Tabla 2, se presentan los resultados de los indicadores estadísticos.

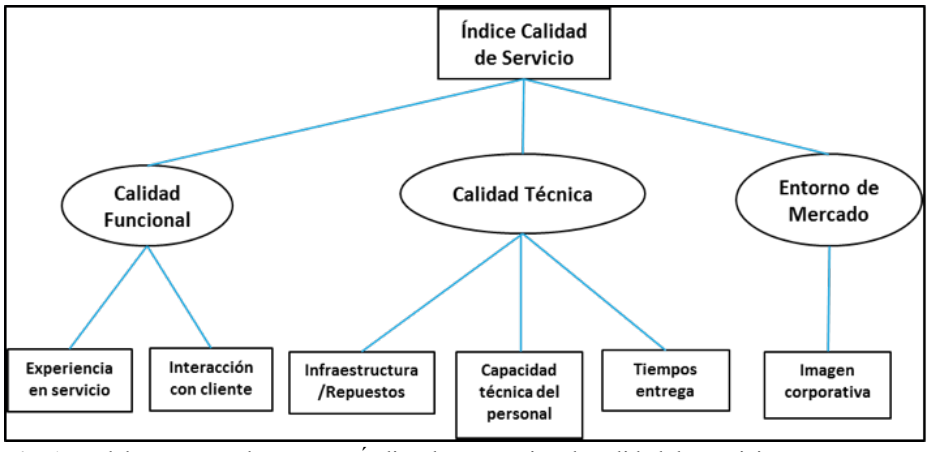

Fig. 1 Modelo conceptual propuesto Índice de percepción de calidad de servicio

Tabla 2. Resumen de indicadores estadísticos

Indicadores	Encuesta piloto
Alpha de Cronbach	0.925
Índice de KMO	0.636
Test de esfericidad	0.000
Factores representa-tivos	3
% Varianza total explicada	74.4%
Determinante de la matriz	Menor a 0.05
Comunalidades	Todas las variables mayores a 0.5

El cuestionario final se aplicó a una muestra de 70 clientes de la empresa Ferroman S.A, correspondiente al 92% del universo de clientes, y fue realizada en un lapso de 1 mes y medio (septiembre-octubre 2017) a través de encuesta presencial, telefónica y por correo electrónico. Los encuestados corresponden a representantes de las empresas que contratan los servicios de mantención de motores eléctricos de Ferroman S.A, siendo éstos de diversas regiones del país incluyendo la Región Metropolitana de Chile. El resultado global del Índice de percepción de Calidad de Servicio global (ICS) obtenido corresponde a 0,86, lo que se traduce en que el estudio presenta un 86% de satisfacción del cliente, lo que esta catalogado como “excelente” según la tabla propuesta por Praxis [10], que clasifica la saistacción de los clientes de los servicios recibidos. Los resultados por factores, se presenta en la Figura 2 y con el objeto de enriquecer la evaluación de los resultados del cuestionario, se realiza un análisis de dispersión y descriptivo de las respuestas que se presenta en la Figura Nº3, donde se muestra que el grueso de los clientes encuestados correspondiente al 83%, se

encuentran en el rango de 4 a 5, es decir, evalúan de forma satisfactoria "algo de acuerdo" y "muy de acuerdo" el servicio otorgado en todas las dimensiones medidas. El restante 17% se encuentra en el rango de 3 a 4, es decir, tienen un nivel de satisfacción menor respecto de la calidad de servicio proporcionada, presentando un cierto grado de desacuerdo con las dimensiones medidas, especialmente con lo relacionado a equipamiento e infraestructura de la empresa, la imagen de la compañía en el mercado, y los plazos de entrega de los equipos.

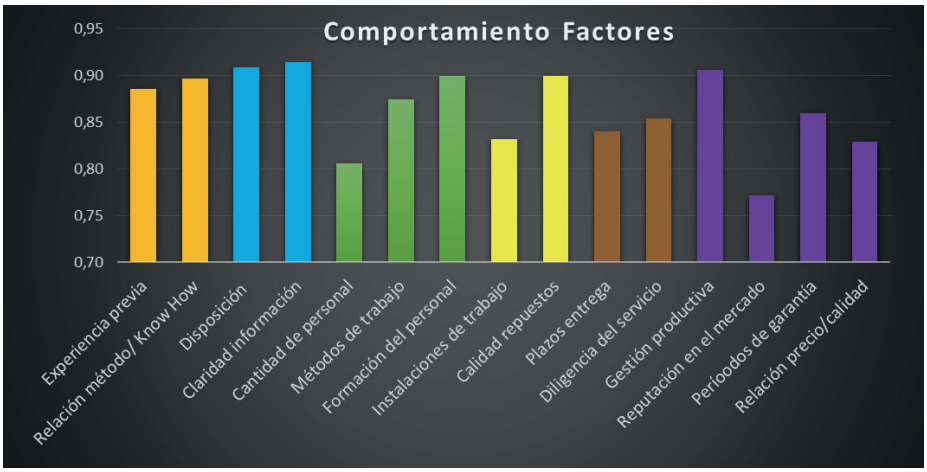

Fig. 3 Resultados obtenidos como porcentaje de satisfacción

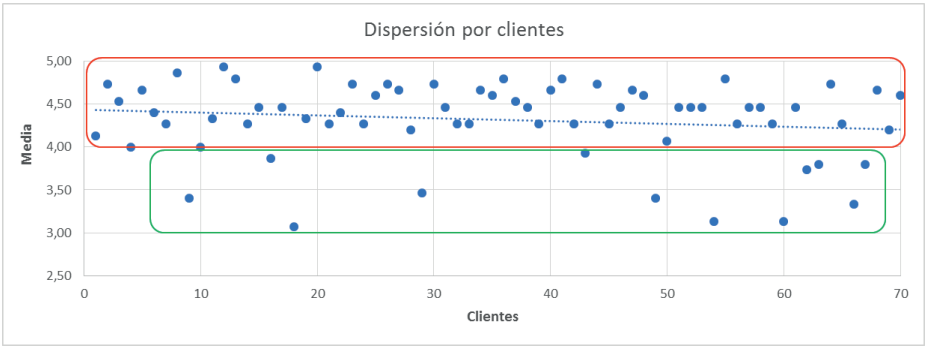

Fig. 3 Gráfico de dispersión de la media por cliente

4 Conclusiones

Al finalizar este trabajo, se concluye que los clientes de la empresa "Ferroman S.A." perciben una excelente evaluación global de los servicios ofrecidos por la empresa, con un Índice de percepción Calidad global de servicio de un 86% de satisfac-

ción. Sin embargo, se debe asumir el desafío de mejorar la experiencia de los clientes en factores como la "cantidad de personal" y "reputación en el mercado".

Del punto de vista metodológico se puede afirmar que el modelo propuesto es confiable y los factores que lo componen son idóneos, lo se validó estadísticamente mediante el indicador Alpha de Cronbach y el Análisis Factorial Exploratorio al cual se sometió el modelo.

Adicionalmente Finalmente, se espera que en futuro se pueda seguir aplicando el modelo con empresas que considere servicios similares al analizado para realizar estudios comparativos de sectores industriales.

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Simulação do agendamento de horários em um restaurante universitário e seu impacto no tempo de espera em filas

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Abstract. Este trabalho tem por objetivo analisar o impacto do agendamento de horário para refeições no tempo de espera em fila em um restaurante universitário. O estudo foi realizado com base no restaurante tipo self-service localizado na Universidade Federal do Paraná - campus Centro Politécnico, o maior polo da universidade atualmente, no qual o tempo de espera em fila externa é elevado em determinados horários. Empregou-se a metodologia de simulação de eventos discretos para reprodução do sistema, sendo os seus procedimentos implementados computacionalmente via MATLAB®. Os resultados obtidos são promissores, indicando que a adoção da política de agendamentos reduz o tempo médio em filas externas, e internas dependendo da distribuição de chegada da demanda, desde que os agendamentos nos horários de menor demanda para a refeição sejam preenchidos.

Keywords: Restaurante universitário; Filas; Simulação discreta; Implementação.

1 Introdução

O setor de prestação de serviços na área de alimentação tem tido uma crescente procura nas últimas décadas, devido o crescimento da urbanização mundial. O consumo de comida não-domiciliar aumentou devido às necessidades do cotidiano urbano-industrial que acabam por reduzir o tempo disponível para preparação do alimento ou até mesmo inviabilizando o deslocamento em decorrência da distância entre trabalho e residência. Assim, em busca da melhoria do gasto do tempo útil, os consumidores procuram um serviço que melhor se adapte a sua necessidade [1,2].

Em muitas universidades públicas brasileiras são oferecidos serviços de restaurantes universitários (RUs), que atendem a sua comunidade acadêmica. Este auxílio oferece refeições de qualidade e com valor acessível, que contribuem para a melhoria do desempenho acadêmico e redução da evasão decorrente da insuficiência de condições financeiras [3]. Na Universidade Federal do Paraná (UFPR), os RUs são do tipo *self-service*, abertos durante toda semana, onde o usuário se serve a vontade e uma única vez. Por sua vez, esse tipo de restaurante tende a apresentar filas, já que a chegada dos clientes ocorre em grupos e em um curto espaço de tempo [4]. Deste modo, reduzir o tempo de espera em fila é de extrema importância.

A adoção de políticas para a redução do tempo de espera nas filas deve ser planejada. Além dos modelos matemáticos e analíticos, uma das ferramentas utilizadas para o estudo do impacto de novas decisões é a simulação [5]. Simular torna possível o estudo do sistema sem que seja necessário construí-lo na realidade, estudando os resultados destas modificações sem que haja necessidade de alterá-lo previamente [6]. As simulações podem ser representações matemáticas, lógicas ou simbólicas, ao qual permitem a análise do modelo sem a necessidade de um sistema real, reduzindo os riscos e os custos que a mudança de um sistema pode causar [7].

Define-se como simulação a imitação de um sistema do mundo real através do tempo [8], enquanto que um sistema é definido como um conjunto de entidades, sejam pessoas ou máquinas, que agem e interagem junto para completar algum final lógico [9]. A finalidade da simulação é realizar um estudo do comportamento de um sistema, verificando o seu desenvolvimento através do tempo de acordo com suas regras/metodologias. Neste estudo, pode-se encarar dois tipos de sistemas de acordo com o tempo, denominados discretos e contínuos: num sistema discreto, o estado das variáveis muda instantaneamente para pontos separados do tempo, enquanto que o sistema contínuo a variável muda continuamente em relação ao tempo [8].

Para simular um sistema de forma efetiva, Banks et al [8] propõe alguns passos para tal: formulação do problema, definição dos objetivos, esboço de um modelo conceitual, coleta de dados reais, abstração do modelo, verificação e validação, design experimental, rodadas com análise, documentação e implementação do modelo. Almejando encontrar um sistema mais verossímil possível, é necessário assumir premissas referentes à operação do sistema que são expressas matematicamente [8], sabendo que a complexidade que um sistema real oferece pode ser mensurada em função do número de processos, filas, recursos, entidades, entre outros [10].

No âmbito de RU, Machado et al [14] objetivou-se a identificar os principais "gargalos" de um RU via *software* Arena®. Santos et al [4] desenvolveu um modelo de simulação do tipo dinâmico, discreto e estocástico, via *software* Arena®, para reproduzir a dinâmica operacional de um pequeno RU do tipo *self-service*, identificando que os *buffets* são o "gargalo" do seu sistema. Oliveira et al [15] avaliou os benefícios da aplicação da modelagem e simulação, via *software* Arena®, para melhorar a performance do sistema de um RU, otimizando os recursos e guarnições do restaurante. Os autores citados tratam o sistema sem alterar a política de organização dos usuários, focando nos recursos dos restaurantes.

Portanto, este trabalho tem por objetivo avaliar o impacto da adoção de uma nova política de organização nos RUs quanto aos seus usuários, especificamente no RU da Universidade Federal do Paraná (UFPR), campus Centro Politécnico, visando diminuir o tempo médio em fila para cada refeição. Este RU, atualmente, possui a maior concentração de alunos da UFPR. O algoritmo de simulação discreta da operação do RU foi implementado via MATLAB®, considerando eventos probabilísticos dos processos realizados pelos usuários, a fim de descrever e analisar o comportamento do sistema, de acordo com uma distribuição de chegada de clientes.

Este trabalho foi dividido em cinco seções. A seção atual retrata as motivações para o estudo. A Seção 2 apresenta uma revisão da literatura do tema. A Seção 3 descreve a modelagem conceitual e computacional adotada para o problema. A Seção 4 ilustra os resultados obtidos na simulação comparando a política atual e a proposta de filas com agendamento. A Seção 5 realiza as considerações finais do trabalho.

2 Revisão Literária

Com o aumento do poder computacional nas últimas décadas, o interesse por técnicas de simulação cresceu, considerando que é possível identificar pontos de melhorias e avaliar diversas soluções sem custo. Tal método é utilizado principalmente para encontrar resultados ótimos para sistemas que possuem filas. O fenômeno de formação de filas é algo rotineiro e ocorre em diversas aplicações, como: uma peça esperando para ser embalada, um avião esperando para decolar, um programa de computador esperando para ser executado, é principalmente e uma fila de usuários esperando um serviço [16]. Tal metodologia também é utilizada durante o desenvolvimento e implantação de um sistema, sendo uma técnica preditiva e preventiva, em que pode-se fazer o estudo de diversas situações e obter respostas para questões situacionais, auxiliando a tomada de decisão e evitando cobranças futuras quanto a situações imprevistas [9]. Assim, esse tipo de análise é uma poderosa ferramenta para a eficiência no processo de produção e pode ser empregada na redefinição de layout ou substituição de controle ou regras de operação, desenvolvimento de sistemas mais eficientes e também aprimorando a solução em problemas de sistemas complexos. O uso do modelo é uma maneira mais barata, segura e conveniente de experimentar ideias [11].

Alguns trabalhos na literatura tratam, por simulação, eventos envolvendo estudo de filas. Por exemplo Fernandes [12] implementou um modelo computacional pelo software Extend®, para simular a dinâmica operacional de uma linha industrial de abate de suínos, validando seu trabalho por meio de dados reais de uma empresa frigorífica. Já Silva [13] desenvolveu uma biblioteca, também via Extend® denominada Grain Facility, resolvendo o problema de armazenamento de grãos em silos, validando seu trabalho utilizando dados reais de uma cooperativa agroindustrial.

De acordo com Law, Hui & Zhao [17], o tempo de espera em fila afeta a frequência de retorno do cliente e é um dos principais pontos no nível de satisfação. O foco na otimização da experiência completa em relação à restaurantes universitários sujeitos à incerteza na demanda e restrições de orçamento foi estudado por Kambli, Sinha e Srinivas [18] que propuseram uma solução baseada em reconhecer onde estão as oportunidades de diminuição nas filas, incorporação de realocação em caso de atraso e a administração da capacidade das filas de acordo com os recursos disponíveis.

Estudos realizados em outros restaurantes universitários identificaram gargalos que impactam muito no tempo de espera. Silva, Gomes e Oliveira [19] concluíram que as principais influências no tempo de espera nas filas da Universidade Federal do Pampa (UNIPAMPA) é o sistema de reconhecimento dos alunos que poderia ser atualizado para um sistema biométrico, sugerindo que um computador com maior capacidade de leitura de dados ou um sistema de fila com prioridade poderá resolver o problema do tempo excessivo na espera sem que sejam necessárias grandes alterações no funcionamento.

Já Oliveira e Costa [20], sugerem que para minimizar os impactos negativos das filas de espera, é necessário avaliar pelo menos três estratégias: o gerenciamento da estrutura do sistema de filas, buscando ajustar a capacidade de atendimento do sistema a demanda de usuários. Geralmente, esta estratégia demanda a expansão de

estruturas físicas e recursos humanos. Em segundo, gerenciamento da percepção de espera, que propõe uma modificação no modo em como os clientes percebem o tempo, tornando a espera mais agradável, como por exemplo, a inclusão de filas múltiplas ou filas expressas. Como o usuário associa tamanho da fila com o tempo de espera, ele pode desistir do serviço antes de perceber a rapidez no atendimento. Por último, a ocultação da percepção de espera possibilita que os usuários executem outras atividades enquanto esperam pelo serviço desejado. Esta estratégia apresenta soluções com baixo custo e resultados relevantes. Um exemplo dessa estratégia, são filas virtuais, que preveem o horário de acesso do usuário baseado no número de pessoas já alocadas na fila e da velocidade de atendimento. A solução proposta foi criar um aplicativo de fila virtual para o RU da Universidade Federal do Maranhão (UFMA).

3 Modelagem

Para o desenvolvimento do modelo conceitual do RU, observou-se como os processos funcionavam na instalação. Após as observações, idealizou-se um modelo conceitual inicial que descrevesse as principais etapas que os usuários percorrem ao utilizar os serviços fornecidos pelo restaurante, como ilustrado na Fig. 1.

Fig. 1. - Modelo conceitual do funcionamento do RU.

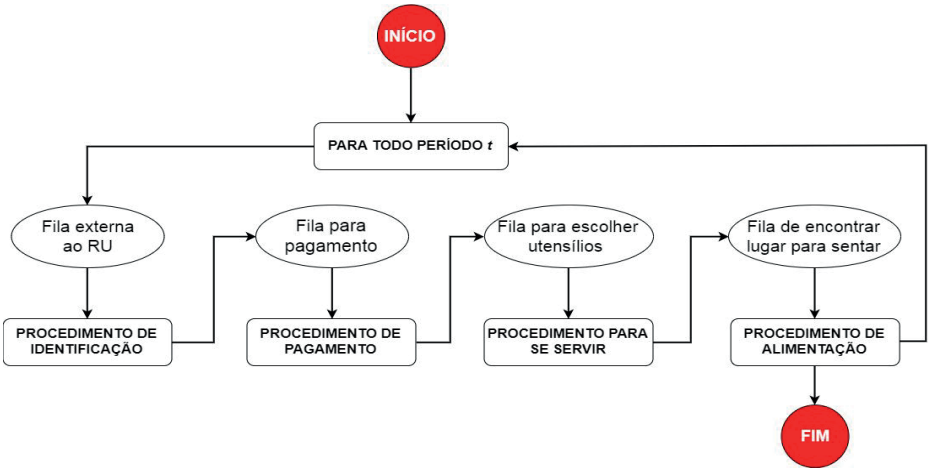


Na Fig. 1, a primeira etapa consiste no processo de chegada. A entrada é realizada em uma fila única formada fora do restaurante, denominada de fila externa. Na segunda etapa, a de identificação pelo Cadastro de Pessoa Física (CPF), as pessoas são direcionadas para *n*-filas, no qual um funcionário verifica a identidade do usuário. É neste momento que são contabilizadas as entradas dentro do estabelecimento. A terceira etapa é o pagamento no caixa. Na quarta etapa, os usuários dirigem-se para os *buffets* de *self-service*, retirando sua bandeja com os alimentos disponíveis. Todas as filas geradas pelas etapas descritas acima serão classificadas como fila interna. Por fim, na quinta etapa, os usuários seguem para as mesas, realizando a sua alimentação e, posteriormente, deixando o local. Todas as etapas foram implementadas e serão descritas a seguir.

A modelagem computacional é baseada na comparação de políticas para entrada no RU. Atualmente, os indivíduos possuem liberdade para se dirigir ao restaurante em qualquer momento, formando uma fila única para o acesso. A proposta deste trabalho inclui a possibilidade de agendamento prévio de horário, cuja entrada no estabelecimento será prioritária em detrimento de quem não agendou, formando duas filas de acesso. Desta forma, este trabalho objetiva-se sugerir uma política para redução, ou pelo menos controle, de tempo de espera em fila externa.

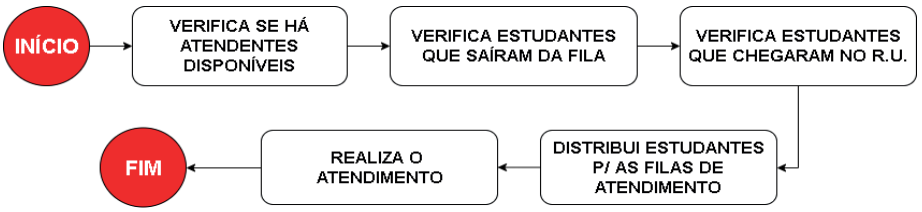
A simulação segue um modelo discreto, no qual verifica-se a cada instante *t* o que está ocorrendo com cada consumidor em cada parte do RU. Antes da realização de um processo (identificação, pagamento, servir ou sentar), o usuário deve passar por uma fila em cada tarefa, como destaca a Fig. 2.

Fig. 2. – Modelo computacional de funcionamento do RU.



O procedimento de identificação possui uma série de passos para a realização, como ilustra a Fig. 3. Inicialmente, confere-se os recursos disponíveis, sendo os computadores livres para que o usuário possa informar seus dados. Em seguida, verifica-se os indivíduos que terminaram o processo de identificação. Então, os usuários seguem para a menor fila disponível, a fim de aguardar o início do atendimento. Posteriormente, os usuários que chegaram no RU são organizados conforme as duas políticas avaliadas no trabalho: filas sem agendamento (política atual) e/ou filas com agendamento (política proposta).

Fig. 3. – Etapa de identificação.



É importante evidenciar que o procedimento de identificação possui uma capacidade máxima, assim como todas as filas de espera em cada procedimento. Esta consideração é necessária para o bom funcionamento de todo o processo do

restaurante, além de ser condizente com as condições físicas no qual o restaurante foi construído. Desta forma, se o limite das *n*-filas de identificação é excedido, a entrada de mais consumidores é impedida até que algum outro usuário finalize sua identificação.

O processo de pagamento inicia-se com a verificação dos recursos necessários para a realização do atendimento dos caixas. Em seguida, confere-se os consumidores que finalizaram o procedimento de identificação no sistema e, então, o usuário se conduz para a menor fila em algum caixa disponível, efetua o pagamento e prossegue para a próxima atividade. A partir do momento que as filas internas atingem sua capacidade máxima, os procedimentos são paralisados, impedindo que os usuários nas filas externas entrem no restaurante. Assim, cria-se tempo para as filas internas diminuírem e o fluxo pode ser retomado. Refletindo o que ocorre no restaurante diariamente.

Finalizado o procedimento de pagamento, os indivíduos são direcionados aos *buffets* para se servirem. No procedimento de se servir, cada usuário aguarda o anterior terminar de se servir em cada setor do *buffet*, análogo ao processo de pagamento.

Após se servir, o indivíduo precisa encontrar um local para sentar-se e alimentar-se, sempre que houver lugar disponível. Este procedimento se inicia verificando os indivíduos que terminaram de se alimentar, liberando-os, e, posteriormente, verificando a existência de lugares disponíveis no instante para o indivíduo que terminou de se servir, destinando-o ao local. Este procedimento também possui capacidade em relação a quantidade de pessoas que podem estar sentadas: caso a capacidade de lugares do restaurante chega ao seu limite, ou seja, não possui mais lugares para os usuários se sentarem, o processo de identificação é paralisado, enquanto todos os outros processos continuam a funcionar normalmente. Deste modo, como não há novas entradas, é possível reduzir a lotação de pessoas dos demais processos até que a quantidade de pessoas em fila seja menor que a capacidade máxima de lugares para se sentar.

4 Experimentos computacionais

A modelagem computacional foi implementada no *software* MATLAB® R2019b, baseada na modelagem conceitual e nos dados disponibilizados pela Pró-Reitoria de Administração (PRA) da UFPR. Os dados, do período de março até junho do ano de 2019, contém registros da quantidade de funcionários disponíveis para realizar a identificação dos usuários, bem como a quantidade de consumidores do restaurante de maior demanda da UFPR, localizado no campus Centro Politécnico. Também foi cedida uma pesquisa, realizada no ano de 2017 pela PRA, para avaliar o tempo médio de refeição dos usuários de uma amostra piloto com 148 observações, durante uma semana nos RUs do campus Central e Jardim Botânico.

Quanto a questões de espaço, o RU adotado possui limitações físicas. Foram consideradas 5 estações para identificações, gerando 5 filas com capacidade de 8 posições cada. Foram considerados 3 caixas para realizar o pagamento, no qual geram 3 filas com 7 posições cada. Quanto aos *buffets*, foram considerados 10, ao qual no máximo 6 pessoas podem escolher cada utensílio e 8 pessoas podem se servir ao

mesmo tempo em cada ilha, respectivamente. A capacidade máxima de pessoas sentadas dentro do RU é de 800 lugares.

Conforme descrito na Seção 2, a simulação é controlada a cada instante de tempo, em que todos os processos são atualizados de acordo com os indivíduos que utilizam cada serviço (identificação, pagamento, servir e alimentação). O horário de operação do RU compreende o período das 11:00 horas até às 13:30 horas. Como alguns indivíduos chegam à fila externa próximo ao fechamento do restaurante, considera-se 30 minutos de "folga" para a simulação, no qual é feita a atualização dos estados e tempos desses indivíduos.

A discretização adotada neste estudo é definida por instantes de segundo. Neste caso, a simulação ocorre em 10800 iterações, equivalente à 3 horas de funcionamento. Esta discretização foi escolhida de forma a descrever o RU com maior precisão, dado que alguns processos dentro da cadeia são mensurados em poucos segundos. Cabe ressaltar que esta discretização é viável no presente trabalho devido ao tempo de funcionamento do RU ser limitado, o que não afeta a eficiência computacional da simulação e possibilita um nível de detalhe maior.

Para os processos de identificação por CPF, pagamento no caixa, servir-se e sentar-se, foram supostas distribuições de probabilidades que descrevessem o comportamento de cada fila, devido ao fato das informações serem escassas. A Tabela 1 destaca as expressões adotadas para geração de números.

Tabela 1. - Expressões adotadas para geração de tempos aleatórios dos processos (em segundos).

Procedimento	Expressão (apenas valores inteiros)
Identificação	TRIANGULAR(4, 6, 8)
Pagamento	TRIANGULAR(2, 3, 15)
Escolha de utensílios	UNIFORME(2,5)
Servir	NORMAL(120, 14^2)
Refeição	TRIANGULAR(420, 900, 3240)

Visto que alguns processos internos do restaurante dependem de expressões de distribuições de probabilidades, existe uma aleatoriedade nas simulações realizadas. Dessa forma, os resultados apresentados neste trabalho foram obtidos como a média de dez simulações diferentes. Cada simulação foi realizada por meio de uma semente aleatória, a fim de possibilitar a reprodução dos resultados.

Para simular a formação da fila externa na entrada do restaurante, é necessário conhecer o comportamento de chegada dos clientes. Optou-se por utilizar o histórico de atendimentos a fim de reproduzir cenários já ocorridos em meses anteriores. Assim, a quantidade de indivíduos que utilizaram os serviços do restaurante é dependente do cenário tomado na simulação, da mesma forma que o fluxo a cada instante de tempo será diferente para cada cenário. No presente trabalho, adotou-se uma série histórica do dia com maior volume de indivíduos, dia 28/03/2019 (quarta-feira), a fim de avaliar o tempo em fila em um cenário de maior utilização de recursos. É possível e foi realizado os mesmos testes com séries históricas de outros dias, porém o presente trabalho limita-se a apresentar os resultados desta única série por questões de formato.

A política proposta consiste na possibilidade do agendamento de horários para refeição. Neste caso, o cliente que agendar um horário terá acesso a uma fila preferencial, que será prioritária sobre a fila comum dos indivíduos que não agendaram. Define-se que a quantidade de vagas é distribuída em intervalos de 15 minutos, constante para os horários. Então, além de analisar o impacto desta política no funcionamento do RU, será possível também verificar o impacto de diferentes números de vagas de agendamento.

Neste estudo, supõe-se que todas as vagas disponíveis para agendamento são preenchidas, independente do instante de chegada original do cliente. No início da simulação, os indivíduos que irão agendar seu horário são sorteados de forma que todas as vagas possuam agendamento, e os instantes de chegada podem ser alterados de acordo com o agendamento. O cliente tentará agendar seu horário próximo à sua chegada original ao restaurante e, caso não exista vaga para o seu horário, escolhe agendar no próximo horário disponível.

Para a computação dos resultados das estatísticas de tempo em fila, registrou-se o instante de tempo em que o indivíduo chega e finaliza cada processo. Isto compreende desde a entrada e saída de todas as filas até o início e fim de sua refeição. Logo, é possível calcular a duração de cada processo durante a passagem do indivíduo no estabelecimento.

4.1 Validação do modelo computacional

A validação do modelo computacional foi realizada baseada no histórico dos dados do sistema de identificação. Neste caso, é possível calcular a quantidade de sujeitos que fazem a identificação no sistema a cada minuto do funcionamento do RU. Desta forma, a validação é feita por meio da medição de quantos indivíduos passam pelo processo de identificação na simulação.

Por meio da computação desses dados, tem-se que a quantidade de indivíduos que se identificam por minuto é constante na primeira hora de funcionamento do RU, decaindo nas horas finais. Além da medição por minuto, considera-se o agrupamento por intervalos de 15 minutos.

Conforme a Tabela 2 mostra, tem-se que a quantidade de indivíduos atendidos nos intervalos de 15 minutos na simulação é semelhante em comparação ao realizado nos cenários.

Tabela 2. - Comparação do fluxo de pessoas da série histórica 28/03/2019 adotadas e sua respectiva simulação.

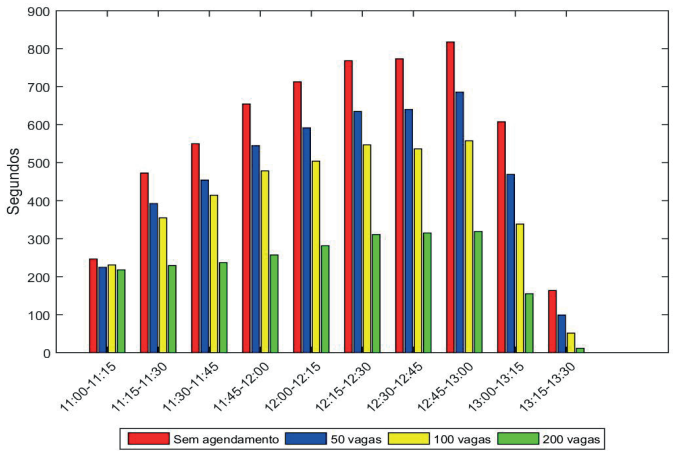
Intervalo (min)	*Real*	*Simulado (média das 10 simulações)*	Erro Relativo (%)
11:00 - 11:15	523	454,7	13,06
11:15 - 11:30	509	434,0	14,73
11:30 - 11:45	484	437,7	9,57
11:45 - 12:00	462	434,4	5,97

12:00 - 12:15	474	438,3	7,53
12:15 - 12:30	463	436,8	5,66
12:30 - 12:45	439	433,3	1,30
12:45 - 13:00	473	440,8	6,81
13:00 - 13:15	266	435,3	63,65
13:15 - 13:30	200	347,4	73,70
		Média dos erros relativos por intervalo	20,2%

4.2 Série de 28/03/2019

Este cenário compreende o dia de maior volume de usuários segundo os dados disponíveis. A Fig. 4 apresenta os tempos médios de espera na fila externa ao RU, por intervalos de tempo e em segundos. É possível observar que houve tempo de espera em todos os intervalos. Quando não há agendamentos, o tempo médio de espera é de 246 (4,1 minutos) segundos quando o RU é aberto, tendo um maior valor de 817 segundos (13,62 minutos) de espera entre 12:45 e 13:00. Próximo ao fechamento do restaurante, no intervalo de 13:15 e 13:30, ainda havia um tempo médio de 163 segundos em fila.

Fig. 4. – Tempos médios de espera em fila externa para cada faixa de horário do dia - Série 28/03/2019.

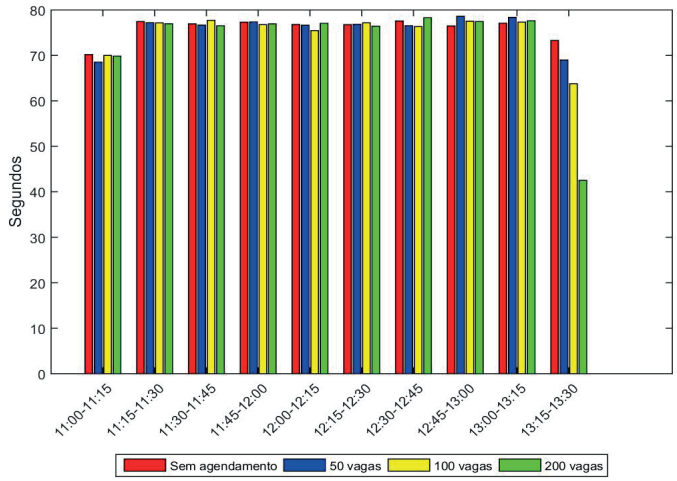


Quando se adota a política de agendamento, observa-se que o tempo médio em fila é reduzido para todos os intervalos analisados. Para o intervalo entre 11:00 e 11:15, os tempos de espera médio são próximos, sendo que a partir de 11:15 essa diferença aumenta. Quanto mais vagas são disponibilizadas para agendamento, maior é a redução do tempo médio em fila externa quando comparado aos tempos da simulação

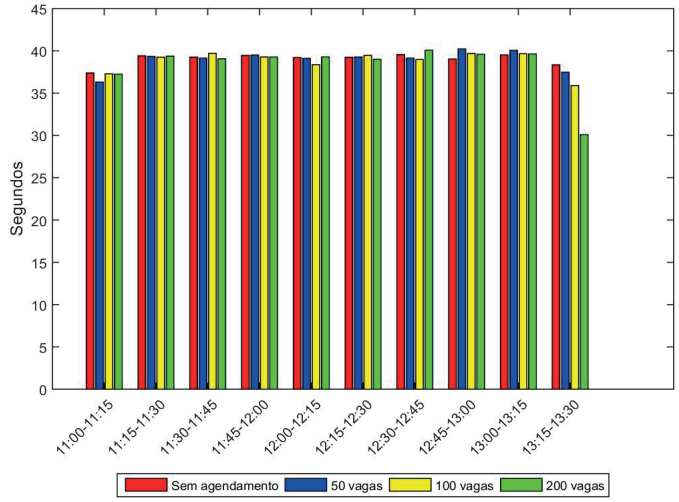
sem agendamento. Como este cenário é o de maior volume histórico, o agendamento não foi suficiente para eliminar a fila externa, mas houve redução no tempo.

Os tempos médios por intervalo para as filas internas do restaurante, filas para identificação, pagamento, e se servir, são ilustradas nas Figuras 5a, 5b e 5c, respectivamente.

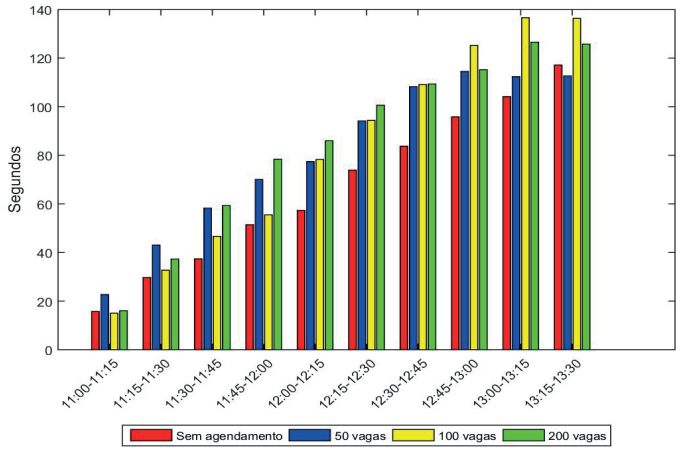
Fig. 5. – Tempos médios dos processos internos realizados pelo usuário - Série 28/03/2019.



(a) Fila de identificação.



(b) Fila de pagamento.

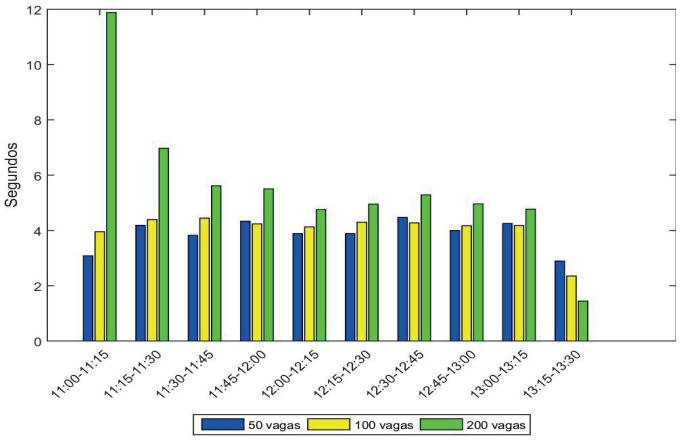


(c) Fila de servir.

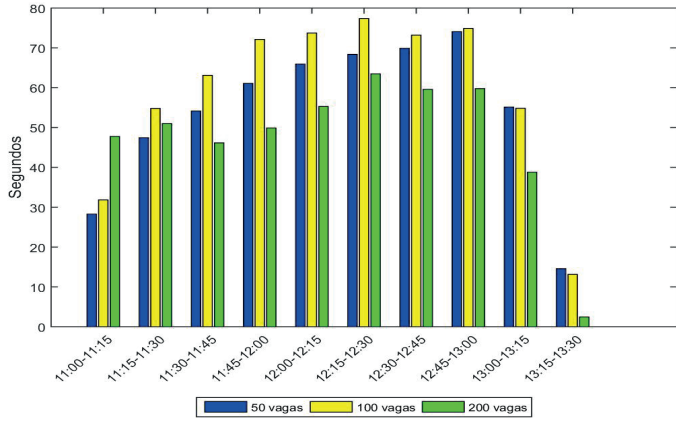
Para este cenário, conclui-se que o agendamento de horários não influenciou no tempo de espera nas filas internas do RU. Isto ocorre provavelmente devido ao alto volume de usuários e a capacidade de funcionários disponíveis para identificação e pagamento não mudar, além da quantidade de *buffets* disponíveis. Nas filas para se servir no *buffet*, observa-se um aumento do tempo médio em fila conforme as faixas de horário. Para a faixa de 11:15 à 11:30, os tempos médios em fila são maiores para os casos em que se considera 100 e 200 vagas para agendamento. Conforme será discutido na próxima seção, este resultado pode ser consequência do aumento do número de indivíduos nessa faixa de horário com a política de agendamento. Além disso, este resultado pode ser um indício de que o processo de se servir obstrui o fluxo do restaurante.

A Fig. 6 compara o tempo médio na fila externa para indivíduos que chegaram com agendamento (Fig. 6a) ou sem agendamento (Fig. 6b) de horário. Neste cenário, é perceptível a diferença entre agendar ou não agendar. Existe uma maior vantagem para os indivíduos agendarem neste caso pois, em média, ficarão 4,5 segundos na fila. Enquanto isso, os indivíduos que não agendaram podem ficar até 775 segundos em fila.

Fig. 6. – Tempos médios em fila externa para cada faixa de horário do dia para indivíduos que agendaram ou não - Série 28/03/2019.



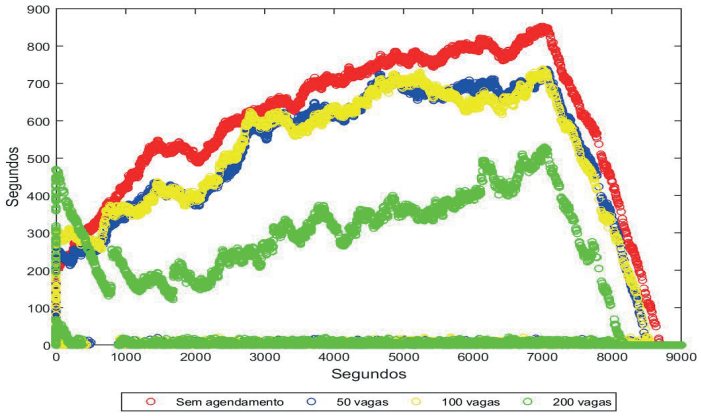
(a) Indivíduo agendado.



(b) Indivíduo não agendado.

A Fig. 7 mostra um diagrama de dispersão entre o instante de chegada do indivíduo ao restaurante e seu tempo de espera na fila externa. Nesta série histórica utilizada, nos primeiros segundos de funcionamento o tempo de espera é maior quando é possível agendar um horário, sendo que a diferença é maior quanto mais vagas são disponibilizadas em comparação quando não existe esta opção. Após um certo horário, tem-se que o tempo de espera em fila é sempre menor para os casos em que uma política de agendamento foi adotada, concordando com os resultados obtidos anteriormente.

Fig. 7. – Horário de chegada por Tempo de espera na fila externa - Série 28/03/2019.

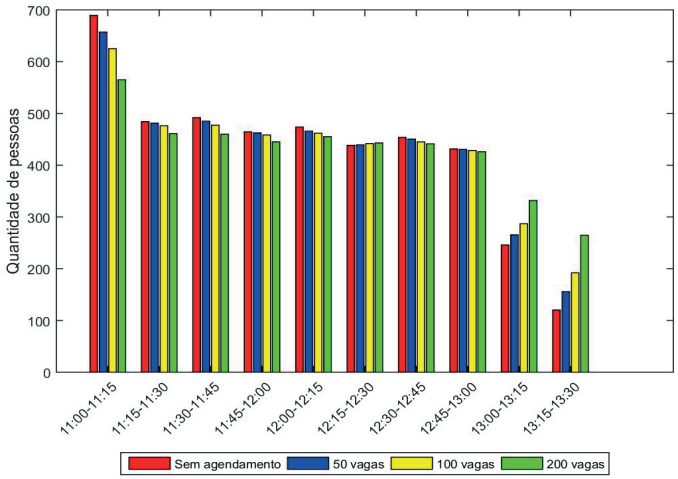


4.3 Impacto da política de agendamento na distribuição de chegada dos indivíduos

Uma consequência direta da adoção da política de agendamento de horários é uma menor concentração de clientes em horários de pico, uma vez que uma parte dos indivíduos são agendados em horários menos procurados. A Fig. 8 ilustra a quantidade de indivíduos que chegaram ao restaurante, por intervalos de tempo, no cenário simulado baseado na série histórica de 28/03/2019. A tendência observada é que, quanto maior a quantidade de vagas disponibilizadas para agendamento, menor é a variação da quantidade de indivíduos que chegam no decorrer dos intervalos. Comparando o gráfico do caso sem agendamento e o caso com 200 vagas disponíveis, percebe-se que a quantidade de usuários nos primeiros intervalos de tempo é reduzida, enquanto nos horários finais aumenta ao considerar o agendamento.

Neste cenário, no caso de 200 vagas para agendamento, a quantidade de usuários que chegam ao RU, especialmente no intervalo entre 13:15 e 13:30, possui 267 indivíduos chegando, enquanto que o cenário sem agendamento 120 indivíduos chegam.

Fig. 8. – Quantidade de pessoas que chegam ao RU - Série 28/03/2019.



Desta forma, a implantação de uma política de agendamento reduz o tempo em fila externa ao restaurante, desde que sejam preenchidos os horários de menor demanda no almoço (a partir de 12:45), pois distribui de forma mais constante a quantidade de indivíduos que utilizam os serviços do RU. Assim, em vez de ocorrer uma concentração maior de indivíduos nas primeiras horas de funcionamento do RU e formação de filas para os processos internos, pode-se distribuir de forma a manter um fluxo constante de clientes e evitar filas, ou pelo menos reduzi-las. Nota-se que para o cenário do dia 28/03/2019 o agendamento reduziu o tempo médio de espera e ainda houve filas no exterior do restaurante.

5 Considerações Finais

Este trabalho apresentou uma simulação do funcionamento de um RU a fim de avaliar políticas para redução de filas. Apesar da simulação ser realizada em situações ideais, em que todas as vagas são preenchidas e os consumidores cumprem o agendamento, pode-se concluir que a política reduz o tempo médio em fila. Para fomentar a adesão dos usuários à política de agendamento de horários no caso do almoço, poderia ser verificado, com base no sistema da universidade, os usuários livres de atividades no período vespertino no campus, permitindo a sua ida ao RU apenas nos horários de menor demanda. Esta tática distribuiria melhor a chegada dos estudantes durante os intervalos de tempo, fazendo com que o agendamento de horários fosse mais concorrido não somente em horários de pico de demanda. Concluímos então, que a política de agendamento de horários reduz o tempo médio em fila, desde que as vagas para agendamento de todos os períodos de funcionamento sejam preenchidas. Os resultados melhoram a experiência do usuário e o fluxo de funcionamento do RU e podem ser replicada para qualquer outro tipo de problema com agendamento em casos reais, na qual a fila aumenta significativamente em determinados horários.

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Generación de valor en el área de Finanzas de una organización de servicios de salud

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Resumen. El objetivo del trabajo consiste en mejorar el proceso de facturación y cobro de una organización de servicios de salud. El principal problema que presenta el Área de Finanzas se origina en el proceso de seguimiento de cobros y reclamos debido a los retrasos en el pago de los servicios prestado, generando inconvenientes de liquidez por no poder afrontar la totalidad de las obligaciones y compromisos financieros en el corto y mediano plazo. Dicha situación pone en riesgo su solvencia futura y supervivencia a largo plazo. El proceso estudiado varía en función de tres modalidades de tratamiento, del tiempo de retraso del cobro y de las diversas formas de pago. Para una mayor comprensión, se estudia la situación actual relevando las actividades que componen el proceso y sus tiempos de ejecución; se identifican las que agregan valor al cliente y la organización, de las que no. Se efectúa un análisis causa-efecto para de detectar los principales motivos que originan el problema. Se formula una propuesta de mejora, que contempla la incorporación de TIC y personal especializado, con el propósito de aumentar el valor agregado para el cliente y la organización. La implementación las mejoras reduce un 71% la cantidad actividades que no aportan valor y aumentan el 33% las que agregan valor al cliente. Disminuye un 60,79% el tiempo de actividades sin valor y aumenta el 7,94% el tiempo que generan valor al cliente. Se concluye que la metodología propuesta genera un impacto positivo para la organización y sus clientes.

Palabras clave: Agregado de Valor, Mejora de Procesos, Servicios de Salud.

Abstract. The objective of this work consists of the analysis and improvement of the billing and collection process of an organization that provides health service. The main problem that the Finance Area presents is originated in the process of monitoring charges and claims due to the delays in the payments of services, generating liquidity drawbacks due to not being able to meet all the financial obligations and commitments in the short and medium term. Such a situation puts it's future solvency at risk and, therefore, their long-term survival. The process

studied varies depending on the treatment modalities provided, the time of delay in debts and the possible forms of payment**.** For a better understanding, the current relevance of the activities that make up the process and their execution times are studied; those that add value to the client and the organization of those that do not are identified. A cause-effect analysis is carried out in order to detect the main reasons that originate the problem. A process improvement proposal was formulated, which includes the incorporation of ICT and specialized personnel, with the purpose of increasing the added value for the client and the organization. The process implementation generates a 71% reduction in the number of activities that do not add value and increases those that add value to the customer by 33%. It reduces 60.79% the time of activities without value and increases 7.94% those that generate value to customers. It is concluded that the proposed methodology has generated a positive impact for the organization and its clients.

Keywords: Added Value, Process Improvement, Health Services.

1 Introducción

La mejora de los procesos y servicios brindados a los clientes se han convertido en una tarea fundamental para las organizaciones que buscan mantenerse en el entorno competitivo actual. Para ello es necesario el desarrollo de una cultura orientada a la gestión de procesos, el trabajo en equipo, la incorporación de tecnologías, la participación del personal y la innovación.

Se toma como caso de estudio a una organización de salud de la ciudad de Mar del Plata que presta servicios especializados en la prevención, atención y reinserción social de personas que hacen un uso indebido de drogas. Frente a la necesidad de mantener la competitividad, liquidez y sostenibilidad futura de la organización y ante las falencias que posee el actual manejo de la información, se considera imperioso la incorporación de tecnologías de la información y de la comunicación (TIC) que sistematicen y faciliten el proceso de seguimiento de cobros y reclamos de la institución y permita la toma de decisiones más certeras al Área de Finanzas y la Gerencia.

El objetivo del presente trabajo es la propuesta de una mejora al proceso estudiado mediante la incorporación de TIC, con la intención de aumentar el valor agregado para el cliente y la organización. Se desarrolla un estudio de procesos para detectar los principales puntos de mejora que aumenten la eficiencia y la generación de valor. Mediante la incorporación de un software de gestión se proyecta proporcionar una herramienta sencilla y sistemática para la ejecución de las actividades del Área Financiera, como así también dotar a la organización de información confiable para la toma de decisiones.

2 Marco Teórico

2.1 Los sistemas de información y el agregado de valor

El estudio del agregado de valor implica analizar los procesos en los niveles estratégico, táctico y operativo de las organizaciones y su cadena de valor. Entre los procesos que crean valor para el cliente se destacan aquellos relacionados con la incorporación de tecnología: por una parte se pueden identificar las que se relacionan con la incorporación intensiva y extensiva de las TIC en las decisiones sobre infraestructura, software, formación y aplicaciones que puedan requerirse en las diferentes actividades de la organización y por otra, aquellas que atañen a las tecnologías emergentes implementadas para la elaboración de productos o servicios. De esta manera, la relación entre las TIC y la generación de valor depende fundamentalmente de la mejora de los procesos de gestión de la información, permitiendo a las organizaciones satisfacer los requisitos de sus clientes y aumentar su desempeño (Albors et al., 2006)

Los sistemas de información permiten a la empresa tomar mejores decisiones, aumentar su eficiencia y brindar mejor servicio al cliente. Desde una perspectiva de negocios, un sistema de información es una importante herramienta que puede generar valor para la empresa y sus clientes. Es por ello, que los sistemas de información, particularmente los softwares de gestión empresarial, permiten que muchas más personas tengan acceso a la información y la compartan, para reemplazar los pasos secuenciales con tareas que se pueden realizar en forma simultánea y mediante la eliminación de tareas repetidas e ineficientes (Laudon y Laudon, 2012).

Para tener un sistema de información apropiado, es conveniente la participación de los usuarios en la definición de los requerimientos ya que facilita la recolección de hechos y contribuciones valiosas. Los usuarios son quienes emplearán el sistema y por ello tendrán un interés legítimo en involucrarse en su desarrollo (Cáceres, 2014)

2.2 Análisis de valor agregado de actividades

Para lograr identificar las actividades que generan un agregado de valor se puede implementar la metodología sistemática propuesta por Miles (1989) denominada Análisis de Valor Agregado de Actividades. Esta consiste en un análisis detallado de cada fase de un proceso para determinar si contribuye a las necesidades o requisitos de las partes interesadas. Persigue la eliminación de actividades que no generan valor en los procesos de la organización, la combinación de actividades que no pueden ser eliminadas y el mejoramiento de las restantes actividades que no generan valor (Hernández Oro, 2012).

En el análisis se deben identificar los distintos tipos de actividades, según se detalla a continuación:

- Actividades de valor agregado para el cliente (VAC): generan valor al cliente y está dispuesto a pagar por ellas.
- Actividades de valor agregado para la organización (VAO): generan valor a la organización y es el resultado del beneficio ofrecido al cliente.

- Actividades sin valor agregado (SVA): no contribuyen a satisfacer a los clientes internos o externos y deben eliminarse o reducirse sin afectar los productos o servicios de la organización. Estas son las actividades de inspección, revisión, espera, archivo y movimiento (Trishler, 1998).

2.3 Herramientas de análisis

Las representaciones gráficas de un proceso contribuyen a mejorar su análisis ya que permiten su desglose en actividades más específicas y detalladas. De esta manera facilita la identificación de las actividades que generan valor a los clientes y la organización de las que no lo hacen. Los diagramas de flujo se utilizan para obtener una visión global de un proceso, son una representación gráfica de la secuencia de actividades que lo conforman y facilitan la identificación de las diferentes áreas que intervienen en cada fase. Para un análisis más detallado de los procesos es necesario descomponerlo en todas las actividades que lo conforman e identificar su tipología o naturaleza. Se emplean los cursogramas analíticos que permiten determinar de forma concreta las actividades de operación, transporte, almacenamiento, demora e inspección; facilitando la identificación de las actividades que generan valor añadido de las que no. Además, estos diagramas, viabilizan comparar los procesos actuales con los desarrollados e identificar concretamente las mejoras obtenidas. Otra herramienta importante para el análisis del proceso es el Diagrama de espina de pescado que permite identificar los puntos críticos o de mejora, determinar las causas que originan los problemas detectados y establecer su relación causa-efecto (Castillo Benavides, 2015).

3 Metodología

Para el desarrollo del presente trabajo y la consecución del objetivo planteado, se adopta una metodología basada en un estudio de caso efectuado en una organización de salud de la ciudad de Mar del Plata.

Los pasos a seguir para su elaboración se enumeran a continuación:

- Paso 1: Caracterización del proceso actual de seguimiento de cobros y reclamos. Se relevan las fases del proceso y sus interacciones mediante la utilización de un diagrama de flujo.
- Paso 2: Análisis del valor agregado de las actividades del proceso actual. Se analizan en forma detallada las actividades que componen el proceso y su naturaleza, con el objetivo de poder distinguir aquellas que aportan valor de las que no. Para ello, se desarrollan cursogramas analíticos derivados del proceso relevado en el paso anterior.
- Paso 3: Identificación de problemas o puntos de mejora. En función del estudio previo, se detectan los puntos críticos del proceso mediante un análisis de causa-efecto utilizando el diagrama espina de pescado.
- Paso 4: Propuesta de mejora del proceso actual. En función de los puntos críticos detectados, se formula un conjunto de mejoras al proceso actual. El proceso con las mejoras propuestas se representa por medio de un diagrama de flujo.

- Paso 5: Análisis del valor agregado de las actividades del proceso propuesto: A partir de la implementación de las mejoras propuestas, se elaboran los nuevos cursogramas analíticos para poder determinar de forma detallada el aporte al agregado de valor del proceso perfeccionado. Se realiza un análisis comparativo del agregado de valor generado por el proceso original y el propuesto.

Para la ejecución de los pasos anteriores se efectúan visitas in situ y entrevistas programadas con los actores involucrados en el proceso analizado. Todos ellos mostraron muy buena disposición y gran interés en participar en las actividades propuestas.

4 Resultados

4.1 La estructura organizacional y las decisiones gerenciales

La organización bajo estudio es una fundación dedicada a brindar un servicio especializado de salud mental para personas que hacen uso indebido de drogas. Posee tres modalidades de tratamiento: hospital de día, de medio día turno tarde y de medio día turno vespertino, cubriendo la franja horaria de 9 a 21 horas de lunes a viernes. Actualmente está trabajando al 75% de su capacidad instalada.

El proceso de servicio varía según las tres modalidades de tratamiento y su duración oscila entre 2 a 3 años, según la evolución de cada paciente. Esta variación se debe a que es un servicio de salud altamente personalizado según las características y necesidades terapéuticas de cada uno. Los tratamientos brindados son cubiertos por obras sociales, prepagas o servicios de salud que posee cada paciente o en caso de no ser así, son abonados en forma particular. La estructura organizacional fue modificándose, desde su apertura en el año 2013, según el crecimiento del número de pacientes atendidos.

El actual organigrama de la empresa se presenta en la Figura 1. Se evidencia una estructura de tamaño pequeño con una departamentalización por funciones. Posee una dotación de 8 trabajadores distribuidos en los diferentes niveles y dos asesores externos.

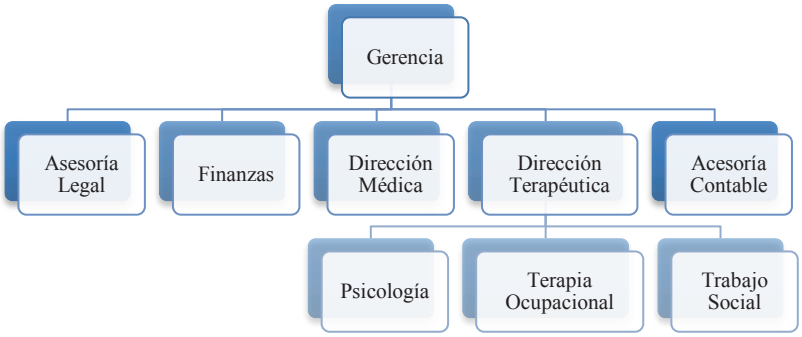

Fig. 1: Organigrama actual.

Las decisiones estratégicas son tomadas por la Gerencia, y en sus comienzos, al ser una organización pequeña esta área también se encargaba de algunas tareas y toma de decisiones de los mandos medios. Debido al incremento de pacientes atendidos estas

decisiones, en su mayoría, han sido delegadas a las áreas correspondientes. Es por ello, que la definición de los lineamientos tácticos y la toma de decisiones de cada área es crucial para el funcionamiento la organización y su sustentabilidad futura.

4.2 El proceso de seguimiento de cobros y reclamos

Actualmente el proceso de seguimiento de cobros y reclamos es realizado por el Gerente de la Fundación con una frecuencia trimestral. El encargado de Finanzas se limita a la práctica de las funciones básicas del área, ya que al desempeñarse a tiempo parcial no cuenta con el tiempo suficiente para efectuar este proceso. Según la cobertura médica de los pacientes, el tiempo de retraso del cobro y la forma de pago, el proceso presenta una serie de variantes. Para una compresión integral de las actividades que lo componen, en la Figura 2, se muestra el diagrama de flujo del mismo.

Como se puede observar, el proceso de reclamos se realiza en función del tiempo de la deuda, la cobertura que el cliente posee, ya sea mediante una Entidad de Cobertura Médica (ECM), si paga el servicio de forma particular o su ECM se lo reintegra luego de realizar el pago correspondiente. Asimismo, existen variantes según la forma de pago, puede ser por cheque o transferencia bancaria. Las actividades de espera que se identifican no dependen de la organización, ya que son tiempos que están en manos de los pacientes o ECM.

Las TIC implementadas en este proceso son escasas y poco eficientes. La documentación y las copias se emiten y archivan de forma física. El registro de los pagos se realiza mediante el uso de planillas de cálculo electrónicas y únicamente están a disposición de las áreas de finanzas y gerencial ya que no poseen un software de gestión integral.

Si bien durante el comienzo de las actividades de la organización el Gerente pudo llevar adelante en forma adecuada este proceso, con el crecimiento de la cantidad de clientes la tarea no se despliega según las necesidades de la organización. La baja frecuencia con que se realiza el seguimiento y reclamo de los cobros y la falta de disponibilidad de la información requerida para el desarrollo del proceso en tiempo y forma son los principales problemas que enfrenta la organización. Esto se traduce en significativas tardanzas en el cobro de los de los servicios prestados, el 92% de los pagos se realizan con retrasos y en el 59% de los atrasos son mayores a los 5 meses, alcanzando en los casos más desfavorables demoras que llegan a 8 meses y más. Este escenario genera inconvenientes de liquidez a la organización, debido a no poder afrontar la totalidad de las obligaciones y compromisos financieros en el corto plazo y, en consecuencia, pone en riesgo su solvencia futura y supervivencia a largo plazo.

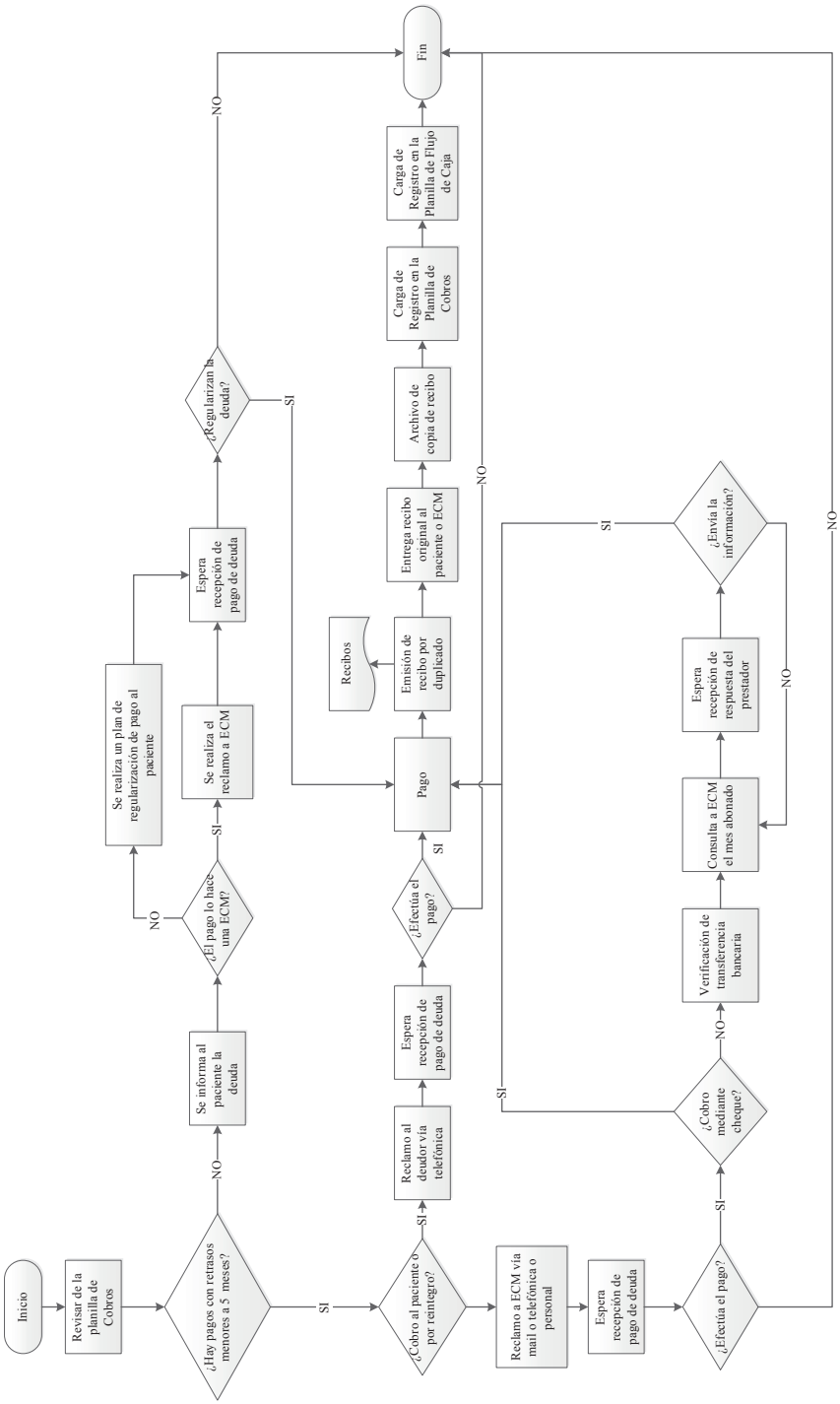

Fig. 2: Proceso actual.

4.3 Análisis del valor agregado del proceso actual

Para la realización del análisis de valor agregado, se realiza un relevamiento detallado de todas las actividades que forman parte del proceso analizado. En función de las diferentes alternativas del mismo se elaboraron cinco cursogramas analíticos con la naturaleza de cada actividad y su aporte de valor.

Se elaboran los cursogramas del:

1. Proceso seguimiento de cobros y reclamos para deudas de más de 5 meses para particulares.
2. Proceso seguimiento de cobros y reclamos para deudas de más de 5 meses para ECM.
3. Proceso seguimiento de cobros y reclamos para deudas de menos de 5 meses para particulares.
4. Proceso seguimiento de cobros y reclamos para deudas de menos de 5 meses para ECM y pago mediante cheque.
5. Proceso seguimiento de cobros y reclamos para deudas de menos de 5 meses para ECM y pago mediante trasferencia bancaria.

A modo de ejemplo, en la Figura 3 se presenta el cursograma del proceso 5. Como se puede observar, existe un importante tiempo de demora por la espera a la recepción del pago de las deudas (1,5 meses).

En la Tabla 1 se presenta el análisis de agregado de valor de los cinco procesos analizados. Respecto a la cantidad de actividades, se puede observar que todos los procesos poseen entre 17 y 46% de actividades sin valor agregado. Al analizar el tiempo de las actividades, todos los procesos reportan casi el 100% del tiempo de actividades que no generan valor.

Analizando los resultados del análisis de valor agregado del proceso total con todas sus variantes, se evidencia que el 30,435% de las actividades no generan valor al cliente ni a la organización, proporción mayor que las actividades que generan valor al cliente (19,565%). En el análisis del tiempo, se observa que solo el 0,042% de las actividades aportan valor al cliente y a la organización y el tiempo total del proceso es de 44.0852,250 minutos, significa que el tiempo de las actividades sin valor agregado representa el 99,958% % del total.

Se determina, que el porcentaje de tiempo sin agregado de valor se origina, en su mayoría, por los elevados periodos de espera para realizar el pago las deudas que varían entre 1,5 a 4,5 meses según el tipo de reclamo. La baja frecuencia con que se efectúan los reclamos y la falta de seguimiento de los mismos contribuyen al aumento de estas demoras.

Cursograma Analítico										
Proceso: Seguimiento de cobros y reclamos para deudas de menos de 5 meses para ECM y pago mediante trasferencia bancaria **Método:** Actual	**Resumen**									
	Actividad						**Actual**		**Propuesto**	**Economía**
	Operación ○						**5**			
	Transporte ⇨						**1**			
	Demora D						**2**			
	Inspección □						**3**			
	Almacén ∇						**1**			
	Tiempo Total [min]						**69.176,25**			
	VAC						**1**			
	VAO						**6**			
	SVA						**6**			

Actividad	**Observaciones**	○	⇨	D	□	∇	**Tiempo [min]**	**VAC**	**VAO**	**SVA**
Revisar Planilla de Cobro para identificar deudores	En planilla electrónica				x		2		x	
Identificación de deuda menor a 5 meses	En planilla electrónica	x					2		x	
Informar ECM de la deuda	Vía telefónica, mail o personal.	x					15		x	
Espera el pago de la deuda				x			65.800			x
Verificación de transferencia bancaria	En banca digital				x		5		x	
Verificación con ECM el mes abonado que se transfirió					x		15			x
Espera recepción de respuesta de ECM				x			4.320			x
Emisión del recibo	En formato papel y por duplicado	x					1			x
Entrega del Recibo a ECM	Original		x				0,25	x		x
Archivo de copia del recibo						x	2			x
Carga de registro en la planilla de cobros	En planilla electrónica	x					7		x	
Carga de registro en la planilla de flujo de caja	En planilla electrónica	x					7		x	
Totales		**5**	**1**	**2**	**3**	**1**	**69.176, 25**	**1**	**6**	**6**

Fig. 3: Cursograma analítico Proceso 5 actual.

Tabla 1. Análisis del Valor Agregado del proceso total actual

Proceso		Actividades				Tiempo (min)			
		VAC	VAO	SVA	Total	VAC	VAO	SVA	Total
Proceso 1	**Cantidad**	3	7	2	**12**	14,250	63,000	103682,000	**103759,250**
	Porcentaje	25,000%	58,333%	16,667%	**100,000%**	0,014%	0,061%	99,926%	**100,000%**
Proceso 2	**Cantidad**	2	5	4	**11**	18,000	21,000	194403,250	**194442,250**
	Porcentaje	18,182%	45,455%	36,364%	**100,000%**	0,009%	0,011%	99,980%	**100,000%**
Proceso 3	**Cantidad**	3	5	2	**10**	11,250	21,000	73442,000	**73474,250**
	Porcentaje	30,000%	50,000%	20,000%	**100,000%**	0,015%	0,029%	99,956%	**100,000%**
Proceso 4	**Cantidad**	1	5	4	**10**	15,000	48,000	69138,250	**64866,250**
	Porcentaje	10,000%	50,000%	40,000%	**100,000%**	0,023%	0,074%	99,903%	**100,000%**
Proceso 5	**Cantidad**	1	6	6	**13**	0,250	38,000	69138,250	**69176,500**
	Porcentaje	7,692%	46,154%	46,154%	**100,000%**	0,000%	0,055%	99,945%	**100,000%**
Proceso Total	**Cantidad**	9	23	14	**46**	43,750	143,000	440665,500	**440852,250**
	Porcentaje	19,565%	50,000%	30,435%	**100,000%**	0,010%	0,032%	99,958%	**100,000%**

4.4 Identificación de problemas

Se realizan entrevistas al encargado de Finanzas y al Gerente de la organización, en las mismas se explicita y detalla el análisis del valor agregado del proceso seguimiento de cobros y reclamos y en base a este análisis se detectan en forma conjunta una serie de problemas o puntos críticos que requieren ser solucionados para mejorar el desempeño del proceso en términos de agregado de valor.

Los principales problemas detectados son:

- El proceso no se realiza de forma sistemática.
- Falta de automatización del proceso.
- El proceso se realiza con una baja frecuencia.
- No se genera documentación digital.
- El envío de documentación en papel y presencial genera demoras.
- Existen demoras en para el cobro del servicio.
- No se efectúa un seguimiento del reclamo una vez realizado.
- El proceso de cobro por cheque o contado genera mayor complejidad y tiempo requerido.
- No existe disponibilidad de información en tiempo real para la gerencia y el área.
- El personal tiene un bajo nivel de capacitación.
- El personal posee sobrecarga de trabajo.
- Existe carga de datos duplicados.

En base a estos problemas, se elabora el diagrama de espina de pescado con la finalidad de organizar esta información en categorías (Figura 4) y facilitar la detección de las relaciones causa-efecto.

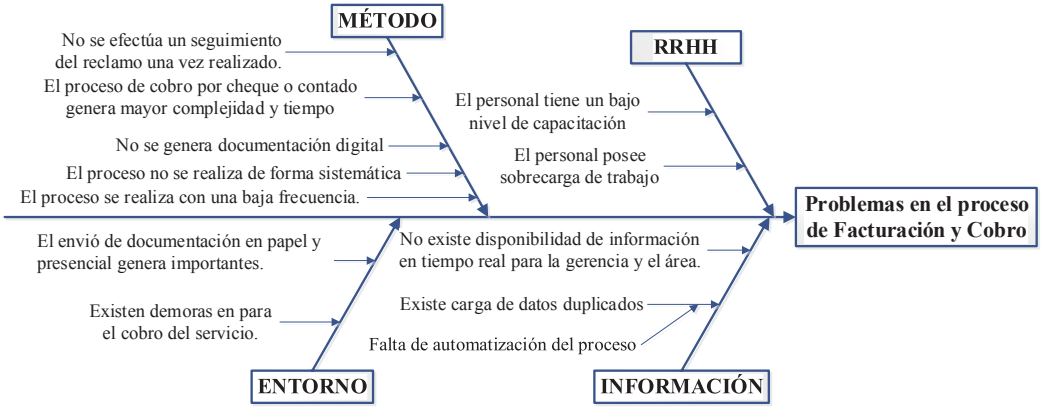

Fig. 4. Diagrama espina de pescado.

4.5 Proceso propuesto

En función del análisis de causas realizado en el paso anterior se proponen las siguientes mejoras al proceso de facturación y cobro de la organización:

- Incorporación de un software de gestión que permita automatizar y sistematizar el proceso, evitar la duplicidad de carga de datos, generar documentación digital y la disponibilidad de información en tiempo y forma para la toma de decisiones.
- Contratar un Contador Público Nacional a tiempo parcial que se dedique exclusivamente al proceso de seguimiento de los cobros y reclamos, como también al de facturación y cobro.
- Realizar la generación y envió de los recibos de manera digital.
- Aumentar la frecuencia de realización del proceso y realizar un seguimiento constante de los reclamos efectuados.
- Adoptar como única modalidad de pago la transferencia o depósito bancario con el objetivo de evitar pérdidas de tiempo y sobrecarga de trabajo al personal.
- Tercerizar el proceso de reclamos de deudas complejas al Estudio Jurídico que efectúa el asesoramiento legal a la organización.

Los problemas originados por el entorno no son posibles de modificar por parte de la organización, debido a que se producen por los métodos de trabajo de las ECM y la capacidad financiera de los pacientes particulares.

Como resultado de los cambios presentados, se presenta en la Figura 5 el proceso de seguimiento de cobro y reclamo propuesto. La incorporación del sistema permite la eliminación de la carga de datos duplicada, la generación de documentación digital y la supresión de las actividades de archivo de documentación. El envío del recibo digital desde el sistema de gestión reduce considerablemente las actividades requeridas en la última etapa del proceso. Se establece una frecuencia mensual para el desarrollo de este proceso y se adicionan actividades para el seguimiento de reclamos efectuados, con el objetivo de reducir los tiempos de espera para la regularización de las deudas. El proceso de seguimiento se realiza luego de esperar un mes a la respuesta del reclamo y posee una efectividad del 70%. Al precisar una única modalidad de cobro, se puede

observar que la supresión del pago con cheque y contado reduce dos variantes, quedando un total de cuatro alternativas del proceso.

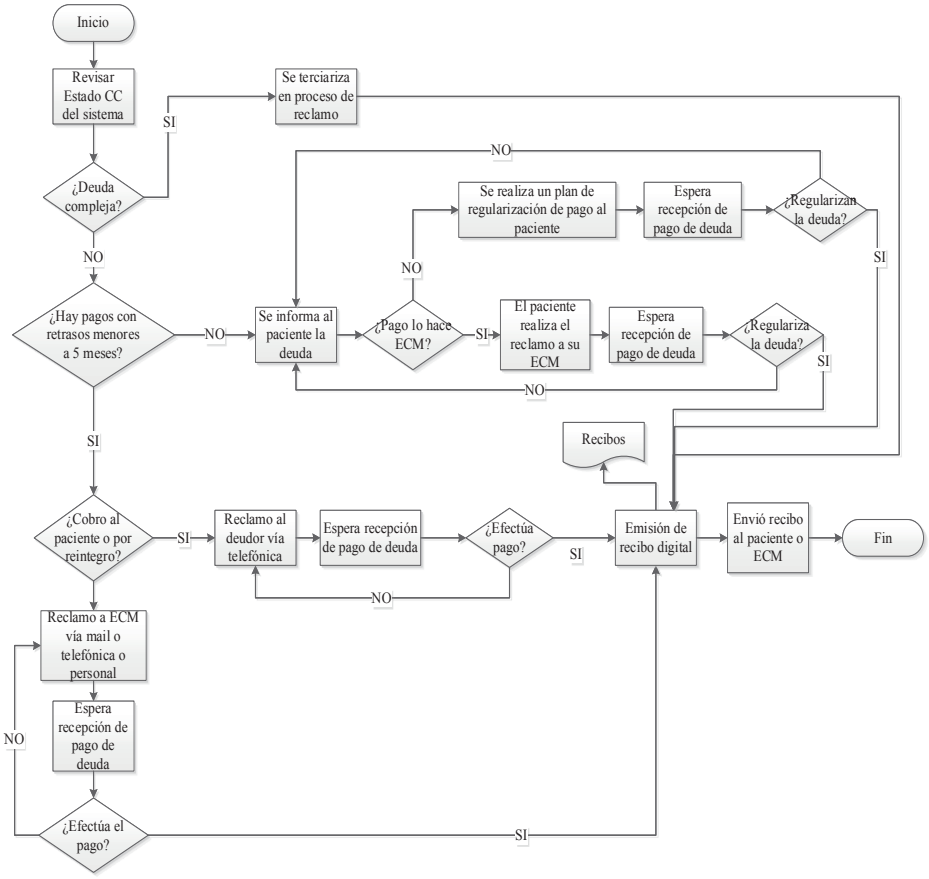

Fig. 5: Proceso propuesto.

4.6 Análisis del valor agregado del proceso propuesto

Luego de la implementación del proceso propuesto, se realiza un relevamiento detallado de todas las actividades con el objetivo de analizar el valor agregado que este genera. En función de las diferentes alternativas del proceso se elaboraron cuatro cursogramas de:

1. Proceso seguimiento de cobros y reclamos para deudas de más de 5 meses para particulares.
2. Proceso seguimiento de cobros y reclamos para deudas de más de 5 meses para ECM.
3. Proceso seguimiento de cobros y reclamos para deudas de menos de 5 meses para particulares.
4. Proceso seguimiento de cobros y reclamos para deudas de menos de 5 meses para ECM.

A modo de ejemplo, en la Figura 12 se presenta el cursograma del proceso 3. Este proceso ha logrado disminuir cinco actividades que no generan valor al cliente ni a la organización y reducir en un 37,52% el tiempo requerido para el proceso.

Cursograma Analítico Operario

Proceso: Seguimiento de cobros y reclamos para deudas de menos de 5 meses para ECM.

Método: Propuesto

Resumen

Actividad	Actual	Propuesto	Economía
Operación ○	5	3	2
Transporte ⇨	1	1	-
Demora D	2	1	1
Inspección □	3	1	2
Almacén ▽	1	0	1
Tiempo Total [min]	69.176,25	43.220,5	25.995,75
VAC	1	2	-
VAO	6	3	3
SVA	6	1	5

Actividad	Observaciones	○	⇨	D	□	▽	Tiempo [min]	VAC	VAO	SVA
Revisar CC para identificar deudores	En sistema de gestión integrado				x		2		x	
Identificación de deuda menor a 5 meses	En planilla electrónica	x					2		x	
Informar ECM de la deuda	Vía telefónica, mail o personal.	x					15		x	
Espera el pago de la deuda				x			43200			x
Emisión del recibo digital	En sistema de gestión integrado	x					1	x		
Envío digital del recibo al paciente	Mediante el sistema de gestión		x				0,5	x		
Totales		**3**	**1**	**1**	**1**	**0**	**4.220,5**	**2**	**3**	**1**

Fig. 6: Cursograma analítico Proceso 4 propuesto.

En la Tabla 2 se muestran los resultados del análisis de valor agregado del proceso propuesto, con todas sus variantes. Respecto a la cantidad de actividades, se puede observar que todos los procesos poseen un porcentaje comprendido entre 12,5 y 16,667% de actividades sin valor agregado. Analizando el tiempo de las actividades, todos los procesos reportan casi el 100% del tiempo de actividades que no generan valor.

Se evidencia que el 14,815% de las actividades no generan valor al cliente ni a la organización, proporción menor que las actividades que generan valor al cliente (44,444%) y a la organización (40,741%). En el análisis del tiempo, se observa que solo el 0,069% de las actividades aportan valor al cliente y a la organización y el tiempo total del proceso es de 172.929 minutos, por lo que el tiempo de las actividades sin valor agregado representa el 99,931% % del total de este tiempo.

El porcentaje de tiempo sin agregado de valor se origina, en su mayoría, por los tiempos de espera para realizar el pago las deudas. Dicha demora es de un mes para

todas las variantes del proceso, que es la nueva frecuencia establecida para la realización del mismo.

Al comparar el proceso propuesto con el original, se observa que la implementación de las mejoras planteadas permite una reducción de un 41,30% de la cantidad de actividades que lo componen y un 60,78% del tiempo total requerido para su desarrollo. Respecto al análisis de valor agregado, se evidencia una reducción del 71,43% de la cantidad actividades que no aportan valor y un aumento del 33,33% de las actividades que agregan valor al cliente. Analizando la variable tiempo, se alcanza una reducción del 60,79% del tiempo de las actividades sin valor y 48,95% del tiempo de actividades que generan valor a la organización, mientras que el tiempo de actividades que generan valor al cliente aumenta en un 7,43%.

Tabla 2. Análisis del Valor Agregado del proceso total propuesto.

Proceso		Actividades				Tiempo (min)			
		VAC	VAO	SVA	Total	VAC	VAO	SVA	Total
Proceso 1	**Cantidad**	3	4	1	**8**	14,500	46,000	43200,000	**43260,500**
	Porcentaje	37,500%	50,000%	12,500%	**100,000%**	0,034%	0,106%	99,860%	**100,000%**
Proceso 2	**Cantidad**	4	2	1	**7**	19,500	4,000	43200,000	**43223,500**
	Porcentaje	57,143%	28,571%	14,286%	**100,000%**	0,045%	0,009%	99,946%	**100,000%**
Proceso 3	**Cantidad**	3	2	1	**6**	11,500	4,000	43200,000	**43215,500**
	Porcentaje	50,000%	33,333%	16,667%	**100,000%**	0,027%	0,009%	99,964%	**100,000%**
Proceso 4	**Cantidad**	2	3	1	**6**	1,500	19,000	43200,000	**43220,500**
	Porcentaje	33,333%	50,000%	16,667%	**100,000%**	0,003%	0,044%	99,953%	**100,000%**
Proceso Total	**Cantidad**	12	11	4	**27**	47,000	73,000	172800,000	**172920,000**
	Porcentaje	44,444%	40,741%	14,815%	**100,000%**	0,027%	0,042%	99,931%	**100,000%**

5 Conclusiones

La metodología propuesta resulta ser efectiva en la mejora del valor agregado del proceso de seguimiento de cobros y reclamos de la empresa analizada. El estudio de procesos ha permitido relevar y analizar detalladamente las actividades que lo componen y ofrece información de entrada para realizar el análisis de valor agregado. Este análisis hizo posible la detección de las actividades que agregan valor al cliente, a la organización y las que no lo hacen, permitiendo identificar los puntos críticos y posibilidades de mejoras del proceso estudiado. En función del mismo, se propone un conjunto de cambios destinados a eliminar los problemas detectados. La incorporación de las TICs al proceso, mediante el uso de un software de gestión, ha reportado un cambio significativo en el método de trabajo, reduciendo actividades innecesarias y duplicadas y permitiendo el acceso a la información necesaria para la toma de decisiones. La incorporación a la organización de una persona capacitada para realizar este proceso ha sido

un cambio fundamental ya que cuenta con los conocimientos necesarios para el desarrollo de las actividades como así también para su continuo análisis y mejora.

Se ha demostrado que la mejora propuesta ha aumentado de forma significativa la eficiencia del proceso y el valor agregado generado para el cliente y la organización. De esta manera, se concluye que la metodología presentada para la generación de valor en el proceso seguimiento de cobros y reclamos ha generado resultados con impacto positivo para la organización y sus clientes, favoreciendo su competitividad y sostenibilidad futura.

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A study on a new hybrid metaheuristic based on the black hole algorithm for clustering problems

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Abstract

Cluster analysis is an active area of research which is applied to a wide range of domains, spanning from physics to neuropsychology. The structure of clustering problems is shown to be hard to solve by exact methods and therefore heuristic procedures are a feasible approach. The present work develops a new hybrid metaheuristic based on the Black Hole Algorithm (BHA), a population-based and nature-inspired algorithm, which is under explored, despite its simple structure and effectiveness. Random local searches are inserted at strategic places of the algorithm and new features added. Results show improvement over the original BHA and related work, thereby rendering the new heuristic procedure competitive. Furthermore, the new approach is easy to implement and requires few parameters. Therefore, it can be used as a competitive alternative to classical algorithms. Computational experiments are run over well-known benchmark datasets as well as newly generated ones. Lastly, future potential research directions are outlined.

Keywords: Cluster Analysis, Black Hole Algorithm, Hybrid Metaheuristics

1. Introduction

Data clustering is a fundamental tool in the data analysis and pattern recognition literature. For instance, its applicability spans from studies on the formation of galaxies [1] to grouping of neuropsychological types of psychiatric patients with bipolar disorder, to assess subjective cognitive difficulties and psychosocial functioning [2]. Clustering is an unsupervised machine learning procedure that seeks to group data in such a way that the dissimilarity between clusters is maximized. Therefore, cluster analysis can be modelled as an optimization problem.

The high computational complexity of clustering problems, which are shown to be NP-hard [3,4], makes approaches that explore all states of the problem to seek for the optimal solution extremely time consuming and therefore unfit. Thus, many heuristic procedures are proposed. These procedures are often classified as hierarchical or partitional [5]. The former works by creating a hierarchy of clusters on the data and iteratively merging similar clusters. The latter, on the other hand, separates data directly into dissimilar and non-empty clusters. Heuristic approaches are especially important for large scale instances and provide good solutions at reasonable running times.

One of the most popular heuristic algorithms for cluster analysis is k-means [6], which works by grouping data points into a given number of clusters such that the sum of squared distances between each point and its nearest centroid is minimal. However, its performance greatly depends on the initial solution provided to the algorithm and convergence at local optima is often verified. To avoid these shortcomings several metaheuristic algorithms are used instead.

Metaheuristic algorithms can be roughly divided into two subgroups: single-based and population-based metaheuristics [7]. Single-based metaheuristics start with a single solution and progress iteratively toward better solutions until no further improvement can be found. Simulated annealing is a very typical example of single-based metaheuristics [8]. It operates based on the annealing process of solid materials and accepts worse solutions with certain probabilities to explore the solution space more thoroughly. On the other hand, population-based algorithms make use of several random initial solutions and optimization is performed on the entire population. A very typical example for the latter category is Genetic Algorithms (GA), which operates based on Darwinian theory of evolution and evolve an entire population until the best solution is found, i.e. the fittest individual among all [9].

Population-based metaheuristics have gained considerable attention over the last decades in cluster analysis problems and have been shown to be very competitive [5, 10, 11]. One of such kind, less explored, is the Black Hole Algorithm (BHA), which is a physics-based metaheuristic and operates according to the functioning of black holes and surrounding stars in the universe [12]. The algorithm works by generating a random population of solutions (stars) at the start, from which the best candidate is selected to be the black hole. The population is evolved by gravitating stars toward the black hole and new ones are generated each time a candidate crosses the event horizon.

In the process, if a candidate happens to be a better solution, then the black hole is replaced by this new solution.

The BHA has been applied successfully in many other optimization problems [13, 15, 16]. Since its inception, however, very few papers have replicated BHA and explored potential hybridizations of the algorithm for cluster analysis, despite its simple structure and effectiveness, which renders the algorithm very attractive from an implementation point of view.

The implementation of hybrid metaheuristics to solve optimization problems is common and successful in many applications. For example, Mageshkumar et al. [17] merges two metaheuristic algorithms, namely Ant Colony Optimization and Ant Lion Optimization, along with Cauchy's mutation operators to increase efficiency in clustering problems. Hybridizations involving population-based as well as single-based metaheuristics are abundant and provide interesting insights to further research on more efficient ways to solve optimization problems.

In this paper, we extend the BHA with random local searches at strategic places of the algorithm, hereafter referred to as BHA-LS. The new hybrid algorithm is tested on several well-known benchmark datasets. Results are compared to the original black hole algorithm [12] to test the feasibility of the algorithm presented in this work. BHA-LS is shown to be competitive in terms of stability, accuracy and running time.

The remainder of this paper is organized as follows. Section 2 describes the clustering problem and a mathematical formulation is presented. Then, in Section 3 the original BHA is discussed and the proposed algorithm is developed in detail. Section 4 describes computational experiments and results. Section 5 concludes with a discussion on future work directions.

2. Problem description

Cluster analysis aims at grouping a set of objects into disjoint clusters such that the similarity of objects within each cluster is maximum. Usually, to evaluate similarity between objects a Euclidean distance metric is used. One might therefore state the problem as follows: given a set of N objects, assign each object to one of M clusters, such that the sum of squared distance between each pair of nodes, is minimized.

Nascimento et al. [18] provides a linearized mathematical formulation to the problem based on a non-linear representation firstly proposed by Rao [19]. The formulation reads as follows:

$$minimize\ F(Y)$$

$$= \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} d_{ij} y_{ij} \qquad (1.0)$$

subject to

$$\sum_{k=1}^{M} x_{ik} = 1, \quad i \; in \; \{1, \dots, N\} \tag{1.1}$$

$$\sum_{i=1}^{N} x_{ik} \geq 1, \quad k \; in \; \{1, \dots, M\} \tag{1.2}$$

$$x_{ik} \in \{0,1\} \quad i \; in \; \{1, \dots, N\}, \; k \; in \; \{1, \dots, M\} \tag{1.3}$$

$$y_{ij} \geq x_{ik} + x_{jk} - 1, \quad i \; in \; \{1, \dots, N\}, j \; in \; \{i + 1, \dots, N\}, k \; in \; \{1, \dots, M\} \tag{1.4}$$

$$y_{ij} \geq 0, \quad i, j \; in \; \{1, \dots, N\} \tag{1.5}$$

The objective function aims at minimizing the distance d_{ij} among all objects that belong to the same cluster. Constraints (1.1) ensure that an object is placed only in one cluster. Constraints (1.2) guarantee that a cluster has at least one object, i.e. is non-empty. Constraints (1.3) state that x_{ik} is strictly binary. Constraints (1.4) and (1.5) ensure that y_{ij} is 1 if, and only if, x_{ik} and x_{jk} are 1, and 0 otherwise. The algorithm developed in this paper is adapted to solve this formulation.

3. Basic concepts and proposed algorithm

The Black Hole Algorithm is a population-based metaheuristic based on the black hole phenomenon [12]. As such, a random population of solutions, called stars, are placed in the search space at initialization. At each iteration, the fitness value of each solution is computed, and the best candidate is selected to be the black hole. Stars gravitate toward the black hole using the following formula:

$$x_i(t+1) = x_i(t) + r * (x_{BH} - x_i), \quad i = 1, \dots, P \tag{2.0}$$

where $x_i(t)$ and $x_i(t+1)$ are the location of stars at iteration t and $t+1$, respectively. x_{BH} is the current location of the black hole and r is a random number in the interval $[0,1]$. P represents the population size.

As the stars gravitate toward the black hole, some of them might achieve a fitness value better than the black hole, and thus the black hole is replaced by the new

star. Also, if a star enters the range of the black hole, i.e. its event horizon, the star is swallowed, and a new random star is generated. This guarantees that the population remains constant with respect to the number of potential candidates. The radius of the event horizon is calculated as follows:

$$R = \frac{f_{BH}}{\sum_{i=1}^{P} f_i} \tag{2.1}$$

where f_{BH} is the fitness value of the black hole, f_i is the fitness value of the i-th star and R the radius of the black hole event horizon. When the distance of a star and the black hole is less than R that star is collapsed and a new one is randomly generated. As described in Soto et al. [14], the death of a star is computed by generating a random number in the interval $[0,1]$, which if it is less than R, computed for each star individually, then a new star is randomly placed in the population.

Here we introduce the concept of relative positions so that the stochastic nature of the previous computation is erased. This allows one to control for solutions that are too close to that one provided by the black hole but with greater costs. The radius of the event horizon is computed as in (2.1) and the relative position (RP) of the i-th star in the universe is calculated as follows:

$$RP_i = \frac{f_i}{\sum_{j=1, j\neq i}^{P} f_j} \tag{3.0}$$

Then, the relative distance between the i-th star and the black hole reads:

$$d_{i,bh} = \frac{RP_i - R}{R} \tag{3.1}$$

If $d_{i,bh}$ is less than a parameter Δ, called the point of no return, then the star dies and a new one is randomly generated. Notice that the diversification of the system can be partially controlled by setting different values of Δ.

When a star is collapsed in upon itself and the formation of a stellar black hole sets off, the material of the dead star is progressively shrunk into a very dense object. Following this principle, when a candidate solution is selected as a new black hole, we introduce a very quick local search, referred to as *Densification*, which is supposed to increase the density of the star, i.e. decrease its cost. The proposed algorithm is as follows:

Algorithm 1 Densification

Input: candidate black hole solution
1: RC = select a random cluster
2: **for** i = 1 to N **do**
3: **if** i is assigned to RC **then**

```
    for j = 1 to M do
        switch object from RC to j
        compute fitness
        if fitness > candidate solution fitness then
            update configuration of candidate solution
            RC = j
        end if
    end for
  end if
end for
```
Output: optimized black hole solution

A stop criterion for the original BHA may be achieved by setting a maximum number of iterations independently of the state of the system, or a maximum number of iterations without improvement. In this paper the latter is chosen to insert a second type of local search into the algorithm.

Physicists teach us that black holes do not last forever since they emit sub-atomic particles. This process is known as Hawking's radiation and is named after the physicist Stephen Hawking. Therefore, if no source of mass is provided to black holes, they would eventually run out of rotation energy and mass, disappearing from existence. As a parallel, in our algorithm, after a certain number of iterations without improvement, i.e. the black hole gets isolated from the system, we introduce a second type of local search aimed at optimizing the black hole solution and make the system active again. This last local search is referred to as *Radiation* and the pseudo-code reads as follows:

Algorithm 2 Radiation

Input: candidate black hole solution
```
for i = 1 to ΩN do (Ω is a real number less than one)
  RN = select a random node in [1, N]
  for j = 1 to M do
    if RN is assigned to j then
      for k = 1 to M\j do
        assign RN to k
        compute fitness
        if fitness > candidate solution fitness then
          update configuration of candidate solution
        end if
      end for
```

```
    end if
  end for
end for
```
Output: optimized black hole solution

The BHA-LS algorithm consists of generating a random population of stars at initialization, set the number of iterations without improvement for operation, gravitate stars toward the black hole and generate new stars according to relative distances, as introduced before. Each time a new black hole is found the *Densification* algorithm is called. By the same token, each time the black hole gets stuck at a sub-optimal state for a certain number of iterations, the *Radiation* algorithm is called. A pseudo-code for the general algorithm is presented below.

Algorithm 3 BHA-LS

Input: random population of stars and dataset
1: δ = initialize number of iterations without improvement
2: counter = 0
3: find black hole among stars
4: **while** counter < δ **do**
5: gravitate stars toward black hole according to (2.0)
6: compute fitness of stars
7: **if** new black is found **then**
8: call *Densification*
9: update configuration of the black hole
10: **else**
11: compute relative position of stars according to (3.0)
12: **for** i to P **do**
13: compute relative distance of star i according to (3.1)
14: **if** $RP_i < \Delta$ **then**
15: generate random star in the place of i
16: **end if**
17: **end for**
18: repeat 11-17 until there are no dead stars
19: **end if**
20: **if** a multiple β of δ has been achieved **then**
21: call *Radiation*
22: **end if**
23: **end while**
Output: final solution

4. Computational experiments and results

4.1 Pre-testing and parameters setting

Pre-testing was executed over 10 small datasets, generated by placing random centroids inside a square and distributing points around each centroid according to a normal distribution. *Instances A* comprise 20 nodes and 2 centroids and *Instances B* comprise 50 nodes and 4 centroids.

The BHA-LS algorithm is made up of four parameters, namely Δ, δ, β and Ω. The point of no return, Δ, was set to 0.25. The number of iterations without improvement, δ, was set to 100. The number of iterations to trigger *Radiation*, β, was set to every 25 iterations without improvement. Lastly, Ω was set to one quarter. During pre-testing it was verified that higher values for Ω did not contribute significantly to quality of solutions and only increased CPU running times. Table 1 displays the optimal values for pre-testing datasets, according to 1.0, the average gap in percentages, the number of optimal solutions found by the algorithm and the average CPU running times in seconds.

Table 1. Results on pre-testing datasets for 100 runs of BHA-LS on each instance.

Dataset		Optimal	Average Gap (%)	Number of optima found	Average CPU Time (s)
Instances A	A.1	8348.6836	3.32	71	0.0013
	A.2	8009.9048	3.44	73	0.0014
	A.3	8201.6025	7.65	79	0.0020
	A.4	6891.7427	12.80	75	0.0016
	A.5	8410.6553	6.81	78	0.0015
Instances B	B.1	32359.9023	3.43	34	0.1675
	B.2	30562.3027	6.57	33	0.1689
	B.3	27175.5898	4.24	43	0.1688
	B.4	27483.0547	3.31	25	0.1639
	B.5	29114.4160	8.27	57	0.1525

4.2 Benchmark datasets

Experiments were run over two groups of benchmark datasets. The first group comprises the multidimensional datasets *Iris*, *Wine* and *Wisconsin Breast Cancer* (*Cancer*), which are public available in the machine learning repository http://www.ics.uci.edu/-mlearn/MLRepository.html. The second group comprises the geometric datasets *Flame*, *R15* and *Aggregation* which are public available in

http://cs.joensuu.fi/sipu/datasets/. Table 2 displays the number of clusters, number of features, number of objects and number of objects per cluster for each of the datasets.

Table 2. Characteristics of the test datasets.

Dataset	Number of clusters	Number of features	Number of objects	Objects per cluster
Iris	3	4	150	(50,50,50)
Wine	3	13	178	(59,71,48)
Cancer	2	9	683	(444,239)
Flame	2	2	240	(87,154)
R15	15	2	600	(40,40, …, 40)
Aggregation	7	2	788	(46,171,103,274,35,131,35)

The performance of the algorithm is evaluated using two metrics widely used in the cluster analysis literature. The first metric is the Error Rate, which measures the external quality of clustering by computing the number of misplaced objects. The second is the Sum of intra-cluster distances and can be seen as an internal quality measure.

The Error Rate is calculated as follows:

$$ER = \frac{number\ of\ misplaced\ objects}{total\ number\ of\ objects} \times 100 \quad (4.0)$$

The Sum of intra-cluster distances reads as:

$$Z = \sum_{i=1}^{M}\sum_{j=1}^{G}\sqrt{\sum_{k=1}^{K}(O_j^k - z_i^k)^2} \quad (4.1)$$

where Z corresponds to the Sum of intra-cluster distances, G is the number of objects assigned to centroid i, O_j^k is the kth coordinate of the jth object, and finally z_i^k is kth coordinate of the ith centroid.

The proposed clustering algorithm BHA-LS was implemented in Java language and run on a computer with an Intel Core i5-7200U CPU @2.50 GHz and 8 GB memory. Results are calculated based on 100 runs of the algorithm and are compared to those in recent literature.

Results on the first group of datasets, and average error rates achieved by the original Black Hole Algorithm [12], are displayed in Table 3. BHA-LS achieved smaller error rates for *Iris* and *Cancer* as compared to the original black hole algorithm [12], which achieved 10.02% and 3.70% for each of the datasets, respectively. Furthermore, still with respect to Error Rate, BHA-LS performed better than the recent work by Abdulwahab et al. [20], in which the authors present a hybrid metaheuristic

with the Black Hole and Levy Flight algorithms and achieved 9.40% and 3.65% error rates, for *Iris* and *Cancer*, respectively. As far as the *Wine* dataset is concerned, the average Error Rate remained roughly one standard deviation above the average Error Rate in [12] and [20]. It is important noting that in both works, the BHA and its variant performed better than well-known population and single-based metaheuristics. On the other hand, the Sum of intra-cluster differences remained slightly above those calculated by [12] and [20].

Table 3. Results on the first group of datasets for 100 runs of BHA-LS.

Dataset	Criteria	Error Rate (%)	Sum of intra-cluster distances	CPU Time (s)	Original BH Error Rate (%)
Iris	Best	6.67	97.51	0.42	-
	Average	9.11	98.19	0.64	10.02
	Worst	12.67	103.73	1.23	-
	Std	0.88	1.39	0.13	-
Wine	Best	28.08	16530.54	0.66	-
	Average	29.33	16667.21	0.98	28.47
	Worst	32.02	17592.37	1.55	-
	Std	0.57	256.3733	0.16	-
Cancer	Best	2.93	2995.55	16.51	-
	Average	3.17	3005.83	22.17	3.70
	Worst	3.95	3061.10	31.88	-
	Std	0.16	11.88	3.19	-

Results on the second groups of datasets are displayed in Table 4. To our knowledge, this is the first time a variant of the black hole algorithm is applied to solve these geometric datasets. The Error Rate averages for *Flame*, *R15* and *Aggregation* are 15.29, 0.45 and 14.46, respectively. The shape complexity of these datasets makes them harder to classify and therefore the performance of BHA-LS has been more limiting as compared to state-of-the-art algorithms [21, 22]. Fig. 1 displays the average solutions obtained to each of the geometric datasets and their corresponding optimal configurations.

Table 4. Results on the second group of datasets for 100 runs of BHA-LS.

Dataset	Criteria	Error rate (%)	Sum of intra-cluster distances	CPU Time (s)
Flame	Best	14.17	772.50	1.02
	Average	15.29	785.84	1.66
	Worst	16.67	796.57	2.68
	Std	0.63	4.40	0.34
R15	Best	0.17	7499.68	47.25
	Average	0.45	7545.55	60.96
	Worst	1.17	7593.11	98.47
	Std	0.19	17.01	7.17
Aggregation	Best	13.58	16943.73	57.30
	Average	14.46	18241.56	87.99
	Worst	15.86	19561.73	134.62
	Std	0.62	394.31	17.68

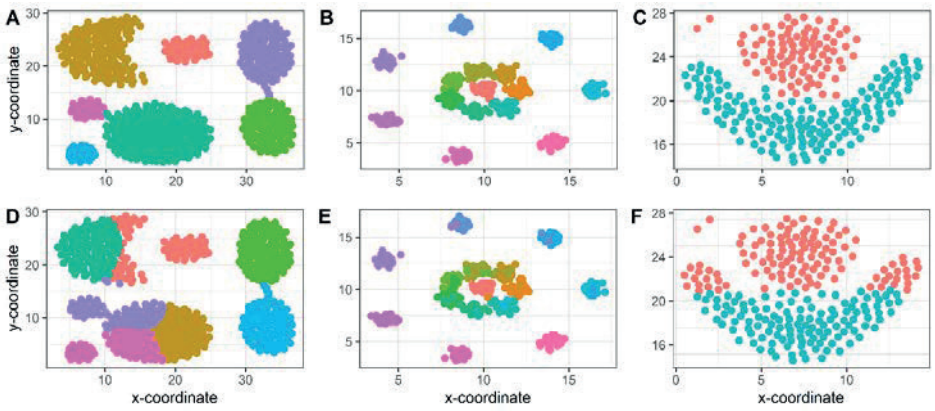

Fig. 1. Plots on the upper half of the figure (A, B and C) are the optimal configurations of datasets *Aggregation*, *R15* and *Flame*, respectively. Plots on the lower half of the figure (D, E and F) represent the average solution obtained by the BHA-LS algorithm for datasets *Aggregation*, *R15* and *Flame*, respectively. Each color inside each plot represents a cluster.

5. Conclusions

This work studied a new hybrid metaheuristic based on the black hole algorithm for clustering problems. The accuracy of the algorithm was tested on well-known benchmark datasets and provided competitive results. The simple structure of BHA-

LS along with its accuracy makes the algorithm an alternative candidate to classical procedures commonly used for cluster analysis. The local searches introduced in the present work are structurally simple, and better approaches can be incorporated into the BHA-LS framework to improve its quality and efficiency. Particularly, the insertion of 2-opt solutions is encouraged in future research, which may boost optimization and improve the structure of solutions. Lastly, the comparison of the framework presented in this paper with state-of-the-art algorithms, such as spectral clustering techniques [23].

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Forecasting Demand in Supply Chain for Automotive Spare Parts: Preliminary Literature Review

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Abstract. Accurate management of information in the links of the supply chain makes it possible to achieve the general objectives of the companies. From this perspective, the determination of demand becomes essential, since each link plans its activities based on market requirements. In the automotive industry, there is a great variety of factors that generate variability in its demand, especially for the spare parts, therefore, determining each product demand becomes complex, due to the fact that auto parts demand is not stable. The using up of methodologies and techniques to analyze the demand is an essential work in the supply chain. Therefore, this work presents a review about papers developed to forecast the demand for automotive spare parts in the supply chain. Also, the document presents alternatives to the decision-makers about the methodologies that can be applied depending on the individual characteristics and objectives of their companies. The classification of the reviewed documents is according to the link in the supply chain and their forecasting method used to solve the problem described in the link, which makes it easier to find the documents according to the interest of readers. Online databases as Elsevier, ScienceDirect, Springer, and Mendeley were consulted. Also, the paper highlights key areas for the future research field.

Keywords: Spare parts, Forecasting demand, Supply chain.

1 Introduction

The supply chain management (SCM) in the auto parts industry is characterized by being complex, due to hundreds or thousands of products with intermittent and variable demand. The demand for these products depends on their positioning in the market and to determine it is very difficult because of the diversity of products. Some factors that determine the high complexity to forecast demand of the automotive spare parts are:

i. The supply of the products, which depends on the origin and type of suppliers, lead time and delivery time, delivery amount, and purchase volumes of products;

ii. The inventory of each product according to the storage and customer service objectives of the company;
iii. The distribution of products based on company policies;
iv. The manufacture of the products, which depends on whether the products are sold directly to the customer or must be assembled within the company;
v. The production capacity;
vi. The life cycle of auto parts and the introduction of new products in the automotive market.

Then, as a conclusion, it is essential to determine the behavior of the demand, aims to obtain accurate forecasts to the needs of the market. Ravindran and Warsing Jr. (2016) consider that the success of a manufacturing supply chain depends on its ability to accurately predict customer demand and produce in time to meet their requirements. Prediction is the starting point for most decisions in supply chain management. An important characteristic of the demand is related to the fact that, whether the demand is externally driven by factors that are outside the direct control of the company, or if it is driven by internal management decisions (Ravindran, 2008).

Therefore, this document is a tool for decision-makers in the supply chain, which help to identify the research works and case studies published from 2010 to 2021, that have similar problems to their situations, which make easier to find alternative solutions in less time and with less effort, as a part of the objective in this document. The documents were classified in books, book chapters, review articles, research articles, web site, magazines, journals, and conference papers published in on-line databases as ScienceDirect, Elsevier, Springer, and Mendeley. The papers were identified under different combinations of keywords such as spare parts, automotive aftermarket, forecasting demand, method and methodologies, supply chain, and its links. From the general query results (2,572 articles), there were selected 291 review articles and research articles by ScienceDirect database, which give more specific information about the published year, journal magazine and access type, in order to give more information to the readers and find key areas for future research.

The paper is organized as follows: Section 2 provides a general literature review about the supply chain in the spare parts industry including automotive. Section 3 presents the selected articles classified according to their subject in the supply chain such as supply, inventory, distribution, transportation, manufacture, production planning and provide some documents, which describe the problems solved on each link and keywords to facilitate the search. Section 4 addressed the literature about forecasting demand in the supply chain in general and for the automotive industry and shows the documents organized according to forecast methods used to determine the demand. Section 5 contains the conclusions and highlight the key areas for future research.

2 The supply chain in the automotive spare parts

According to Lokad (2019) the automotive aftermarket industry expects to achieve in 2020 a global value of over USD $700 billion by selling approximately 80 million of automobiles, because today the customers realize the importance of the preventative maintenance and regular services of their cars to increase their lifetime. The automotive spare part is a big industry in the world and all of the links in this supply chain work together to achieve the objectives of the companies.

Sabri and Beamon (2000) define a supply chain as "a set of facilities, supplies, customers, products and methods of controlling inventory, purchasing, and distribution", where each element plays an important role from the raw material to the finished product (from supplies to customer). Mentzer et al. (2001) said the supply chain makes it possible that the customer gets auto spare parts according to their expectations; considering that the supply chain has organized its links to obtain the results planned. According to Mehdizadeh (2020), it is important to consider two kinds of spare parts: i. spare parts for automotive production and, ii. spare parts for maintenance service of the cars, which is well known as the aftermarket industry; both of them have a similar supply chain, however the behavior of their demands are different.

The first one depends on the production of the new car models and the second one depends on the cycle of life of the spare parts and the maintenance of the cards in the market. Matsumoto and Ikeda (2015) named the last one as remanufactured products or the aftermarket. This work considers the documents found on the database for both types of spare parts, which is based on selected information from on-line databases as Elsevier, ScienceDirect, Springer, and Mendeley. They classified their documents in different types of publications: web site, magazine, chapter, conference paper, books, reviews articles, article, and research articles. The keywords used, to select the articles from the databases, were "forecasting demand for spare parts", which got the maximum result 3,853 documents (books, reviews articles, and research articles) from 1997 to 2021.

The period was reduced from 2010 to 2021 in order to get the most recent documents, obtaining 191 review articles and 1358 research articles. Figure 1 shows the distribution of the articles published.

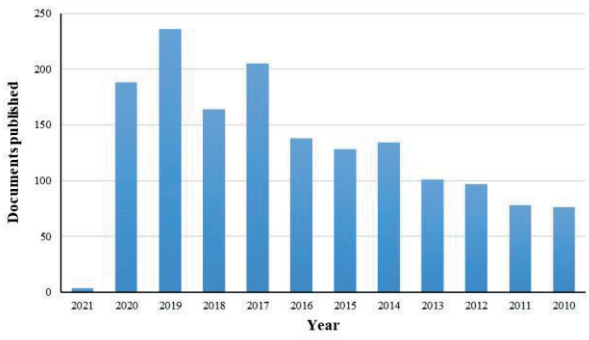

Figure1. Distribution of articles published. Source: ScienceDirect Database (2020)

The documents were accepted for its publication in the International Journal of Production Economics, Journal of Cleaner Production, Renewable and Sustainable Energy Reviews, Procedia CIRP, Energy Policy, European Journal of Operational Research, IFAC-PapersOnLine, Technological Forecasting and Social, and Computers & Industrial Engineering Energy.

3 Forecasting demand for automotive spare parts and supply chain links

As it was mentioned previously, papers were identified under different combinations of keywords such as spare parts, automotive aftermarket, forecasting demand, method and methodologies, and supply chain and its links. From the general query results (2,572 articles), there were selected 191 review articles and research articles by ScienceDirect database, which give more specific information about the published year, journal magazine and access type.

Table 1 shows the results got from the combination of the keywords considering the period from 2010 to 2020.

Table 1. Results of search on ScienceDirect database

KeyWord	Review article	Research article
Spare parts forecasting demand	191	1,358
Forecasting demand for automotive spare parts	310	277
Forecasting demand for automotive aftermarket	7	59
Methodology forecasting demand for automotive spare part	34	187
Method forecasting demand for automotive spare part	42	249
***Method forecasting demand for automotive spare part and Supply Chain**	**33**	**182**
Logistic	18	79
Inventory	27	151
Manufacture	41	205
Production	40	234
Suppliers	27	154
Transport	27	133
Distribution	39	195
Planning	37	215
Planning, suppliers, inventory, distribution, production, manufacture, transportation	13	47

Source: ScienceDirect database (2020). * The keywords were combined as: “Method forecasting demand for automotive spare part” and the link in supply chain.

Behnam (2018) said that product forecasts are a critical input into the supply chain, finance, and marketing decisions, also he wrote a literature review about judgmental demand forecasting with an approach focused in the integrating of forecasting methods. He considers the role of expert opinion and contextual information and show the application of behaviorally informed support systems. The literature is focused on the industrial practice. Stip et al. (2019) comment that it is normal that customers have services contracts, including agreements on spare parts supply for their companies.

Zhu et al. (2019) considers that spare parts demand forecasting is essential to spare parts inventory control, however, it is very difficult to determine the demand because of its feature of irregularity during the time; they propose a forecasting procedure to estimate the spare part demand behavior based on a maintenance plan, this forecast let to develop a dynamic inventory control method. Also, Rodrigues et al. (2020) consider that the quality of future demand forecasting determines the performance of any inventory control model. If the forecast demand is accurate then, the safety inventory level is low and the fill rate increases. They show an approach for a spare parts inventory control model for non-repairable items with periodic review, where the demand behavior varies over time. V. Lukinskiy et al. (2020) considers that “Inventory management is one of the most important logistics functions”, where is important to determine the optimal stock (current, safety) levels and optimal order quantity of all products in the company and determine the adequate inventory management strategies; Also, in their work, they show a characterization of papers on demand forecasting and inventory management, where they describe the methodology used to solve the problem, the aim of the document, and a general description of the document.

Mehdizadeh. (2020) and Rego et al. (2015) consider that a good part of the research is focused on to determine forecasting consumers’ demands; also Mehdizadeh (2020) said that "better forecasting of consumers’ demands helps the retailers place more accurate orders to the distributor". However, the retails consider in their warehouses the products with fast-moving and some middle-moving products trying to decrease the backorders and reduce the lost sales cost, they look for decreasing the ordering cost such as freight and insurance and inventory hold cost (Goodarzi et al., 2017). Therefore, the distribution and inventory of products depend on accurate forecasting demand in both links.

Ottosson et al. (2019) predict future demand with causal-based fore-casting methods using condition monitoring data, considering fault codes, as explanatory variable. Furthermore, an evaluation is made on what effects its implementation would result in a transport company. Similarly, Stip et al. (2019) studied the service Bill of Material (BOMs) in a large Original Equipment Manufacturer in the semiconductor industry. They developed a method to generate alerts for possible fails or errors during the operations, which generates a multiple sources of machine information for determining the demand of the spare parts.

Ansersson et al. (2018) in their work "explore and propose how product-in-use data can be used in, and improve the performance of, the demand planning process for automotive aftermarket services". They recognize the relevant product-in-use data and

divides them into categories considering different life cycle phases and demand frequencies. Also, they find relevant areas of application of product-in-use data in the demand planning process, and on their performance effects.

Table 2 shows an article classification according to the Supply Chain approach. The classification contains the articles from the original search which were published from 2017 to 2020 and their relevance in the link of the Supply Chain because some of them cover more than a link. Also, the classification has a general description of the paper and the keywords which the author considers important on the paper. The keywords are added to facilitate the new search by the readers.

Table 2. Article classification according to the Supply Chain approach

Approach	Author	Description	Keywords
Supply Chain	Zhu et al. (2020)	Simple forecasting mechanism to estimate the spare part demand distribution based on the maintenance plan, and develop a dynamic inventory control spare part demand forecasts.	Spare parts inventory control, Spare parts forecasting, Maintenance planning.
	Sharma et al. (2017)	The methodology helps to optimize the maintenance activities and forecasting the requirement of spare parts both before and during the mission.	Mission reliability, Simulation, Genetic algorithm, Army Failure simulation, Spare parts forecasting.
	Rosienkiewicz M. et al. (2017)	The hybrid spares demand forecasting method dedicated to mining companies.	Spare parts, Demand forecasting, Artificial Neural Networks (ANN), Information Criterion, Bayesian Information, Mining industry.
	Ali et al. (2017)	Strategy for evaluating a simple Downstream Demand Inference (DDI) strategy based on Simple Moving Average (SMA) for supply chains where information cannot be shared.	Supply chain management, Information sharing, Simple moving average ARIMA, Downstream demand inference.
	Mobarakeh et al. (2017)	The document presents forecasting methods, their variants, and artificial intelligence (AI) methods developed for irregular demands, which the propose is to determine the best method variant that is capable of accurately forecasting not only uncertain but unpredictable demand in a business aircraft.	Spare parts supply chains, Demand forecasting, Boot Strapping, Business Aircraft's industry.
Logistics	Dombi et al. (2018)	A methodology for modeling and forecasting spare part demand for electronic commodities in the spare parts logistics services.	Spare part logistics; electronic aftermarket, services; purchase life-cycle forecasting; knowledge discovery; clustering time series.
	Boutselis et al. (2018)	Application of Bayesian network models for forecasting the demand for spare parts in the last phase for the logistics service system.	Bayesian networks, Failure rates, Spare parts forecasting, changing demand context.

	González et al. (2017)	A comparison among classic methods of moving averages, final value and exponential smoothing, the prestigious autoregressive integrated models of moving averages (ARIMA), the rarely implemented artificial neural networks (ANNs) and the very little explored ARIMA-ANNs hybrid models.	Demand Forecasting, Supply chain management, Forecasting hybrid models, ARIMA-ANN performance comparison, Automobile spare parts logistics.
Inventory	Stip et al. (2019)	A method to generate alerts for possible errors and determine the Bill of Material (BOM) per installed machine and determine the inventory of spare parts.	Configuration management, Spare parts, Inventory management, Forecasting, Data science.
	Zhu et al. (2020)	Develop a dynamic inventory control spare part demand forecasts.	Spare parts inventory control, Spare parts forecasting, Maintenance planning.
	Rezaei et al. (2018)	Inventory optimization based on a mathematical model to minimize the total investment subject to fill rate as an inventory service measure at both part and location level.	Business aircrafts' spare parts management, Uncertain and unpredictable demand, Lead-time demand distribution, Inventory optimization, Inventory parameters estimation, simulated annealing.
	Zhu et al. (2017)	The empirical method by applying extreme value theory to model the tail of the lead time demand distribution to improve the performance of the inventory.	Forecasting Inventory, Spare parts, Extreme value theory Semi-parametric.
	Teixeira et al. (2017)	The document presents a multi-criteria classification of a spare part for integration in a computerized maintenance management system of a manufacturing company, the methodology defines groups for which a stock management policy will be associated.	Inventory management. Maintenance management, Multi-criteria classification, Spare parts, Spare parts management.
	Sharma et al. (2017)	The methodology helps to optimize the maintenance activities and forecasting the requirement of spare parts both before and during the mission. Also, it determined the requirement by having a forecasting technique for reducing the supply lead times.	Mission reliability Simulation, Genetic algorithm, Army Failure simulation, Spare parts forecasting.
	Hu et al. (2017)	Literature review of OR in spare parts management according to a framework for OR in spare parts management, established based on the product lifecycle process.	Inventory, Spare parts management, Operational research (OR).
	Costantino et al. (2017)	A model for a single site the Zero-Inflated Poisson (ZIP-METRIC)is built for Spare parts management for irregular demand items.	Inventory management, Logistic, Intermittent demand, lumpy demand, Zero-Inflated Model.
	Bergman et al. (2017)	An approach was developed for demand forecasting using Bayes' rule to improve the forecast accuracy of parts from new equipment programs.	Intermittent demand, Bayesian forecasting, Engineering estimates.

Manufacture and production planning	Stevenson et al. (2005)	A review of production planning and control and spare parts.	Production planning and control; Make-to-order; Job shop; Small and medium sized enterprises; Workload control.
	Israel et al. (2017)	A Process of predicting equipment failures and Intelligent Maintenance System.	Supply Chain, Spare Parts, Intelligent Maintenance Systems, Integrated Planning, Discrete event simulation.
	Stip et al. (2019)	A method to generate alerts for possible errors and determine the Bill Of Material (BOM) per installed machine in the field.	Configuration management, Spare parts, Inventory management, Forecasting, Data science.
	Yufune et al. (2020)	A demand forecasting model regarding the replacement as probability event for maintenance planning.	Remanufacturing, Mining machine parts, Demand forecasting, Hydraulic pump, Simulation.
	Andersson et al. (2018)	To explore and propose how product-in-use data can be used in, and improve the performance of the demand planning process for automotive aftermarket services	Forecasting, Big data, Digitalization, Aftermarket, Demand planning, Product-in-use.
	Gu et al. (2017)	A double-level combination forecasting approach for repairable spare parts based on relevant data for airplanes.	Demand forecasting, Repairable airplane spare parts, Double-level combination forecast, Genetic neural network, Exponential smoothing, Grey model.
Transport	Otosson et al. (2018)	Predict future demand with causal-based forecasting methods using condition monitoring data, specifically fault codes, as explanatory variable in a transport company.	Forecasting, Spare part logistics, Condition monitoring data, Fault codes, correlation analysis, regression analysis.
Distribution	Alfieri et al. (2017)	Two allocation policies are proposed to use a dynamic critical level to reserve on-hand inventory for high priority customers.	Dynamic critical level, Multiple demand classes, Distribution–free policy.

The results in Table 2 show that the links manufacturing, production planning, and inventories have more articles developed about demand forecasts for spare parts. On the other hand, for Distribution and Transport articles there are only few of them. This results show the importance of the accurate forecast demand on those link, also the impact on the supply chain.

4 Forecasting demand for automotive spare parts

Knowing the demand in each link of the supply chain is a fundamental part of achieving success for the companies. For the spare parts management to forecast demand is an important operational issue, and it has been a big challenge. For Israel et al. (2019) spare parts demand is sporadic and erratic, which impairs its forecasting with available statistical tools and damaging service level and potentially increasing production costs in the industrial sector.

V. Lukinskiy et al. (2020) argue that authors are skeptical about the forecasting and accuracy of the demand, because, in some situations, it is possible to identify base demand for a product which is predictable but in other cases, the demand is unpredictable and uncertain. Also, Sillanpää et al. (2018) consider that probabilistic models based on distribution forecasts help to determine the demand when there is a lack of accuracy in the planned orders of the consumer.

Petropoulos et al. (2014) in their work studied fourteen popular forecasting methods and some combinations with them, seven time-series features (seasonality, trend, cycle, randomness, number of observations, inter-demand interval, and coefficient of variation) under one strategic decision: the forecasting horizon; take into a count intermittent demand data as namely average inter-demand interval, squared coefficient of variation of the non-zero demands and number of available observations. Petropoulos et al. (2015) explored empirically the efficiency of forecast combinations in the intermittent demand context by using a combination of time series. And, Petropoulos et al. (2016) built the heuristics which predict the demand and reduce the variance in the times series by transformed time series and the inverse intermittent demand series.

Babai et al. (2019) propose a new forecasting method that is a modification of the Syntetos and Boylan approximation. The forecasting of intermittent demand is studied under the classical forecasting studies methods, but the majority of these studies do not take into account underlying demand-generating factors (Van Steenbergen et al., 2020). In addition, the application of forecasting methods is limited because the available data; also, the factors influencing spare parts demand are different because of the phases of the lifecycle of the products; in this case, Van Steenbergen et al. (2019) presented an innovative demand forecasting method with name DemandForest, which is a mix of K-means, Random Forest, and Quantile Regression Forest, based on the historical sales data of previously introduced products and product characteristics of existing and new products; the objective of the method is predict the total demand and its patterns of a new product during the introduction period. According to Turrini et al. (2019), "spare parts forecasting is divided into parametric and non-parametric approaches", where non-parametric methods normally based on bootstrapping procedures which evaluate the percentiles of the distribution from the data, also they explain that parametric forecasting considers a certain distribution of the lead-time demand which it is estimated directly from the data through an estimation method.

Hasni et al. (2019) developed a literature review about parametric and the non-parametric approaches, where they describe the bootstrapping approach and discuses some of its statistical properties. Also, they consider that bootstrapping methods show a good empirical performance in comparison with their parametric counterparts, and they confirm the accuracy of bootstrapping methods for intermittent demand forecasting should be a priority for spare parts management. Yufune et al. (2020) proposed a demand forecast model considering a Weibull distribution as a probability event of the replacement of the spare parts, and they simulated the demand obtained in the mining machinery operation. Matsumoto et al. (2016) proposed a model mix Weibull distribution and Holt-Winters model to obtain the forecast demand of automotive electric components. Also, Matsumoto and Ikeda (2015) proposed a demand forecasting model by using time analysis specifically double exponential smoothing method. Babai et al. (2020) proposed a Bayesian method based on compound Poisson distributions, in which the performance of the non-parametric method improves for longer lead-times and higher demand variability when compared to the parametric one. Geda et al. (2018) developed a similar study based on Bayesian estimation to propose a forecasting model of product returns using DLM using negative binominal function and Markov Chain Monte Carlo. Gonzalez et al. (2017) made a comparison between traditional time series methods and ARIMA-ANNs (autoregressive integrated moving average - artificial neural networks) and they conclude that, in terms of implementation, the classic methods are the easiest and fastest to start to work. Also, and the classical methods provide good results when faced with fluid behavior in demand. However, the ANN (artificial neural network) methods promise good results and presented a good fit for the sample period but began to fail in the erratic post-sample periods, as it was found the literature.

Table 3 shows the articles obtained from the original search which were published from 2017 to 2020 and they were chosen according to their objective and relevance in the link of the Supply Chain too, organized in descending order. Also, Table 3 shows the method used to analyze the demand and the objective of the paper, to make it easier to choose the document by the reader.

Table 3. Documents of forecast demand spare part from 2017 to 2020.

Author	Method (s)	Objective
Yufune et al. (2020)	Time series analysis and simulation.	To build a demand forecasting model regarding the replacement as probability event.
Otosson et al. (2018)	Regression forecast.	To predict future demand with causal-based forecasting methods using condition monitoring data.
Dombi et al. (2018)	Clustering time series.	To build a methodology, which mainly advantageous in long-term forecasting, it is useful in supporting purchase planning decisions in the ramp-up and declining phases of purchase life-cycles of product-specific spare parts.
Boutselis et al. (2018)	Bayesian network models.	To determine the demand using Bayesian network models for spare parts.

Andersson et al. (2018)	Causal-based forecasting methods.	To explore and propose how product-in-use data can be used in, and improve the performance of the demand planning process for automotive aftermarket services.
Zhu et al. (2017)	Extreme value theory.	To determine the lead time demand periods computed over overlapping intervals.
Zhijie et al. (2017)	Mathematical model.	To establishes a general model for predicting the consumption of equipment spare parts based on unit life.
Sharma et al. (2017)	Simulation and Genetic algorithms.	To use simulation for predicting failures in the army equipment.
Rosienkiewicz M. et al. (2017)	Regression modeling and ANN.	To propose a hybrid spares demand forecasting method dedicated to mining companies.
Ali et al. (2017)	Single Exponential Smoothing and Simple Moving Average (SMA) method.	Developing a strategy for evaluating a simple Downstream Demand Inference (DDI) strategy based on Simple Moving Average (SMA) for supply chains where information cannot be shared.
Mobarakeh et al. (2017)	Artificial intelligence (AI) method and Boot strapping method.	To investigate forecasting methods, their variants and artificial intelligence (AI) methods, developed for irregular demands.
Gu et al. (2017)	Genetic neural network model.	To build a double-level combination forecasting approach for repairable spare parts.
González et al. (2017)	ARIMA-ANN models.	To compare methods for determining the automobile spare parts demand.
Bergman et al. (2017)	Bayesian forecasting.	An approach was developed for demand forecasting using Bayes' rule to improve the forecast accuracy of parts from new equipment programs.

Based on the results in Table 3, the papers developed about the forecast of automotive spare parts are few, this shows an opportunity area for the research and expert in this knowledge field. Also, this is evidence that papers developed in this field involve the combination of various knowledge areas such as mathematics, statistics, management, engineering, and supply chain, just to mention some.

5 Conclusions and future research

Determining the behavior of demand in any productive sector is a fundamental job. The selection of a suitable forecasting method determines the achievement of the decision-makers' objectives. Therefore, the forecasting method selected should be as precise as possible and letting decision-makers eliminate uncertainty at any point in the supply chain. The selection of the forecasting method is a complex task, for this reason, this document shows some of the documents that have been developed until now, in order

to forecast the demand in some link of the supply chain, as well as show some methodologies developed that can be applied in any sector, providing greater tools for decision-makers in organizations.

The documents considered in the results section belong to publications made from 2017 to 2020, taking into account their relevance in some link in the supply chain and their year of publication. The database consulted for this purpose was ScienceDirect, since it was the one that provided the most detailed search for the selection of articles.

As shown in the results of Table 2, the links in the supply chain with the highest number of publications made on the topic of demand forecasts for spare parts are manufacturing, production planning, and inventories, because these links support a large part of the productivity of companies, without detracting from the work carried out in the other links of the supply chain.

From the above, we can propose new lines of research in the remaining links, guiding organizations to seek greater integration of the links in the supply chain, since the forecast of demand for each link has an integral impact on the chain. In addition, the results show that the documents developed in this area of knowledge, specifically for the automotive sector, are not very extensive, so it represents important opportunity areas for researchers and experts, considering the economic activity that this sector represents in the real world.

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Atributos em modelos de maturidade para cadeias de suprimento inteligentes

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Resumo. Os modelos de maturidade auxiliam as empresas a avaliarem e classificarem o desempenho de determinada área ou processo organizacional. Dentro de cada modelo de maturidade os atributos também devem ser avaliados para direcionar a avaliação feita. Uma grande área oportuna para a aplicação é dentro da logística, nas chamadas cadeias de suprimentos. Contudo, as mudanças pelas quais as empresas estão passando internamente com o advento da Indústria 4.0 incentivam um novo estudo a partir dos modelos já existentes para atualizá-los, de acordo com as novas demandas dos mercados, que indireta e/ou diretamente afetam o desempenho dos processos de uma organização. Os modelos de maturidade também conseguem ajudar a empresa no planejamento e organização, uma vez que mapeiam seus processos atuais e fornecem uma direção para que seu objetivo seja alcançado: a melhoria contínua. Tendo isso em mente, inicialmente nesta pesquisa foi feita uma revisão bibliográfica em algumas bases de dados para que pudesse ser estudado modelos de maturidade - relacionados a *Supply Chain* e Indústria 4.0 - publicados, bem como seus eventuais *gaps*. Assim, após uma grande análise e discussão dos resultados obtidos após a revisão, ao final desta pesquisa foi desenvolvido um novo modelo de maturidade que relaciona questões e processos importantes das empresas atuais. O modelo elaborado é apresentado brevemente neste documento e ainda será testado em uma indústria do setor automotivo.

Keywords: Modelo de Maturidade, Indústria 4.0, Cadeia de Suprimentos.

1 Introdução

A Cadeia de Suprimentos (*Supply Chain*, em inglês) já era muito conhecida no século XX. Em 1991, o termo foi definido por [1] como aquele responsável por integrar "cada elemento do processo de produção e suprimento, desde as matérias primas até o cliente final". Segundo [2], a cadeia de suprimentos de uma determinada empresa pode ser definida como uma série de atividades interligadas que abrangem a coordenação, o planejamento e o controle de produtos e serviços entre fornecedores e clientes**.**

A integração da *Supply Chain* no desempenho organizacional tem papel importante e é relacionada tanto à integração interna quanto à integração de fornecedores e de

clientes [3]. A mesma ideia foi defendida por [4], ao afirmar que as atividades do processo devem ser integradas internamente e posteriormente com negócios parceiros.

De acordo com [5], a colaboração entre seus membros gera um menor custo total e melhor desempenho do serviço. Além disso, para [6], as demandas do mercado por menores custos, flexibilidade, capacidade de resposta e maior qualidade devem ser atendidas pela cadeia de suprimentos.

Para que saibam lidar com o aumento dos desafios de gerenciamento, as empresas devem tornar-se mais inteligentes [7]. Ferramentas que conseguem auxiliar as previsões dentro da *Supply Chain* mesmo com os riscos inerentes, como incertezas de demanda e informações disruptivas, são extremamente importantes para a logística pois conseguem torná-las mais flexíveis e inteligentes nas operações feitas [8]. Uma das formas de se tornarem mais espertas, com maior habilidade de gerenciamento, consiste na adoção das novas tecnologias digitais provindas da Indústria 4.0.

Dentro do gerenciamento da cadeia de suprimentos (*Supply Chain Management*, em inglês, ou SCM, abreviado) é possível fazer a adoção de algumas técnicas que auxiliam no gerenciamento como *Big Data Analytics*, RFID e manufatura aditiva [9]. As empresas capazes de adquirirem essas habilidades, criadas pelo uso das tecnologias digitais, terão vantagens em relação aos seus competidores e concorrentes que não aproveitarem [10]. Como as disrupções de mensagens e tecnologias digitais influenciam no SCM, os pesquisadores estão voltando os olhos para os temas nas últimas duas décadas, pois como ambas influenciam na SCM é coerente esperar integrações entre os dois assuntos [9].

Quando falamos de Indústria 4.0, termos como *Digital Supply Chain* (DSC), *Smart Factory* e *Smart Supply Chain* (SSC) podem ser utilizados para caracterizar esse cenário quando trata-se de um entendimento comum. O que pode se afirmar é que as tecnologias digitais já estão presentes e todos estes termos tentam explicar como elas irão transformar os atuais modelos de negócios [11].

Pelo fato das tecnologias já estarem ingressando os chãos de fábrica, os benefícios são evidenciados quando uma companhia planeja-se para integrar o mundo físico com o das informações, reduzindo lead times, flows de produção mais definidos a partir de uma demanda prevista de acordo com flutuações do mercado e aumentando as relações entre fornecedores e clientes [12].

Os principais destaques da Indústria 4.0 podem ser apontados como *Big Data*, *Cloud Computing, Internet of Things* (IoT) e customização em massa [13]. A aplicação da Indústria 4.0, com suas respectivas tecnologias, dentro da cadeia de suprimentos de uma empresa pode ser feita de forma variável. Ela consegue ser sistematizada de forma pontual, como no uso por RFID, de forma local, quando utiliza-se do IoT ou de forma global, quando fala-se da interconectividade entre as cadeias de suprimento de uma mesma empresa [10].

Visto isso, ressalta-se a necessidade de utilização de métodos avaliativos que ofereçam um diagnóstico dos elementos e processos da cadeia moderna. Como exemplo, a empresa Basis melhorou seus processos e atingiu o nível 5 de maturidade do modelo CMMI [14], que se refere à melhoria contínua dos processos das organizações por meio de inovações e melhorias tecnológicas [15].

Dessa forma, notando-se os diversos benefícios advindos dos modelos de maturidade e o impacto das tecnologias disruptivas, este artigo objetiva fazer uma análise da revisão bibliográfica, a fim de identificar os modelos de maturidade utilizados e encontrar possíveis *gaps* ou necessidades que precisam ser atendidas no contexto de *Supply Chain* e Indústria 4.0. Além disso, no final deste documento é apresentado um novo modelo de maturidade que ainda será testado e aplicado em uma empresa do setor automotivo.

Metodologia

Primeiramente foi feita uma busca na literatura por artigos e estudos relacionados ao tema de Modelos de Maturidade e Cadeia de Suprimentos. Para isso foi necessário definir quais bases de dados seriam utilizadas para tal. Foram definidas: *Web of Science*, *Scholar*, *Science Direct* e *Scielo*.

Em seguida, foram definidas as palavras-chave que seriam utilizadas para realizar a busca dos artigos nas bases de dados. Nessa etapa, as palavras foram testadas e verificou-se se o resultado obtido com a busca estava de acordo com o tema da pesquisa. Por fim, as palavras-chave definidas foram: *maturity model AND supply chain*; mat*urity model AND indust* 4.0*; *maturity model*; *maturity level**; *technolog* AND maturity model*.

Após a definição das bases e das palavras-chave, os artigos encontrados foram filtrados para que fossem excluídos artigos repetidos. Além disso, a pesquisa teve como foco maior os artigos com data de publicação mais recente, porém isso não excluiu artigos anteriores muitos relevantes a esta pesquisa. Dessa forma, para a revisão buscaram-se artigos publicados desde 2015, sobre o tema proposto.

Após concluída essa primeira etapa de busca, foi feito uma leitura mais aprofundada dos artigos, e foi possível refinar os resultados obtidos, verificando se o título e o resumo de cada artigo estavam condizentes com o tema proposto. Os artigos que não seguiam a linha da pesquisa foram descartados.

Os artigos restantes foram lidos integralmente. Os que estavam de acordo com o tema foram mantidos e selecionados para formar o portfólio final, e os que não estavam seguindo o tema foram descartados. A metodología apresentada está representada de forma visual na Figura 1.



Fig. 1. Fluxograma da metodologia seguida neste estudo

Os artigos relevantes foram selecionados e compilados em uma planilha para melhor visualização. Nessa planilha também foram destacados os pontos-chave de cada artigo, tais como: título, ano de publicação, autores, palavra-chave utilizada na busca e objetivo do artigo.

Com essa base organizada, foi possível partir para a próxima etapa, mapear os atributos e níveis utilizados por cada autor em cada modelo de maturidade apresentado. Vale ressaltar que os atributos e níveis observados nos modelos em questão, foram analisados e dez modelos de maturidade principais foram selecionados, os quais são o foco central deste estudo. Por fim, baseado nos modelos selecionados, foram feitos três quadros, o primeiro com a nomenclatura de cada modelo de maturidade, o segundo com a relação dos níveis utilizados nesses modelos e o terceiro, que apresenta os atributos utilizados pelos autores desses modelos e a frequência com que eles aparecem em cada modelo selecionado.

2 Revisão da Literatura

2.1 Modelo de Maturidade

Com base em dados coletados em sua pesquisa, [16] mostraram que existe uma relação significativa entre a cadeia de suprimentos de uma empresa e as vantagens competitivas que podem advir dela. Além disso, pode-se perceber o quanto é crucial o papel dos diferenciais competitivos no mercado atual [16]. Nesse cenário, é necessário que as organizações evoluam dentro de suas cadeias o conceito de maturidade dos processos para gestão [17].

Modelos de maturidade ganharam destaque nos últimos anos e são responsáveis por proporcionar a melhoria sistemática e contínua de desempenho do aspecto analisado [18]. Evidências mostram que as empresas podem melhorar o desempenho da sua cadeia de suprimentos por meio da criação e desenvolvimento de um modelo de maturidade [19]. Embora, inicialmente, os modelos de maturidade não estejam ligados diretamente aos processos da cadeia de suprimentos, nos últimos anos ocorreram diversas pesquisas sobre o tema, em que era representado o uso dos modelos tomando como base os KPIs (*Key Performance Indicators*) para analisar e medir o desempenho das operações da cadeia [20].

Percebeu-se que, apesar de existirem tipos variados de modelos de maturidade, apresentados no Quadro 1, inclusive alguns bem recentes, que baseiam sua abordagem especificamente numa cadeia de suprimentos, apenas um autor, [21], aborda diretamente as tecnologias da Indústria 4.0 como medida de avaliação para nível de maturidade, com foco nas tecnologias. O modelo de maturidade considerando as tecnologias 4.0 foi publicado em 2016. Porém, como o mundo sempre passou por transformações que exigiram o progresso, e até hoje o reflexo dessas mudanças influenciam nosso dia a dia [22], faz-se necessário identificar como as novas tecnologias podem influenciar a maturidade da cadeia de suprimentos no momento atual.

Quadro 1. Principais modelos de maturidade encontrados por meio da revisão da literatura feita

Número de Referência	Nome do Modelo de Maturidade
[17]	Supply Chain Management Maturity Model (SCM³)
[36]	Supply Chain Capability Maturity Model - S(CM)²
[37]	Quality Management Maturity Grid (QMMG)
[38]	Demand management maturity model
[21]	Industry 4.0 Maturity Model
[39]	Supply Chain Maturity Model - SCM²
[35]	Maturity Model for Supply Chain Flexibility
[40]	Fuzzy analytical hierarchy process (FAHP)
[41]	Classification tree for supply chain maturity model
[20]	Business Process Orientation Maturity Model (BPOMM)

O termo maturidade pressupõe a evolução de um estado inicial até um estado final, em que existe um desenvolvimento dos processos, através de estados intermediários da maturidade [23]. Ademais, a maturidade pode ser definida como o momento em que uma empresa alcança a condição ideal para atingir suas metas. Essa condição é atingida por meio do desenvolvimento das operações, passando por vários estágios intermediários [24]. Os modelos de maturidade também definem que o progresso em direção ao sucesso e à realização dos objetivos definidos ocorre em etapas [17].

A estrutura de um modelo de maturidade tem como principais objetos: níveis, dimensões e atributos. Dimensões são "áreas específicas que descrevem diferentes aspectos do objeto de avaliação de maturidade" enquanto os níveis são "arquétipos da maturidade do objeto que é avaliado" [25]. Os níveis variam de acordo com o modelo de maturidade e respectivos autores. O Quadro 2 mostra uma relação da quantidade e nomenclatura dos níveis encontrados nos modelos de maturidade selecionados pelos autores deste artigo.

Quadro 2. Níveis dos modelos de maturidade destacados na revisão da literatura

Número de Referência	Quantidade de níveis no modelo	Descrição do nível mínimo	Descrição do nível máximo
[17]	5	1. Ad Hoc	5. Estendido
[36]	5	1. Indefinido	5. Conduzindo
[37]	5	1. Incerteza	5. Certeza
[38]	4	1. Transacional	4. Avançado
[21]	5	1. Incompleto	5. Exemplar
[39]	5	1. Nunca ou não existe	5. Sempre ou existe
[35]	5	1. Sem flexibilidade; Paradigmático	5. Flexibilidade
[40]	5	1. Não estruturado	5. Otimizado
[41]	4	0. Sem gerenciamento da cadeia de suprimentos	3. Liderança, trabalho em equipe, entre outros
[20]	5	1. Ad Hoc	5. Estendido

O Quadro 2 mostra que os modelos analisados apresentam entre 4 e 5 níveis e, que a maturidade da cadeia de suprimentos pode ser analisada considerando diferentes aspectos. Os processos dentro de uma Cadeia de Suprimentos necessitam de modelos de gerenciamento e avaliação que, orientados ao desenvolvimento, resultam em melhores níveis e melhores formas de medir o progresso. Transformar em números os níveis de maturidade de uma empresa por meio de um modelo representa uma oportunidade dessa empresa de solidificar seus indicadores e seus processos de melhoria e tornar sua estratégia mais competitiva [20].

Assim sendo, pode-se dizer que um modelo de maturidade visa proporcionar o entendimento acerca do nível em que uma empresa se encontra, dentro das dimensões e atributos definidos. Cada avanço de nível de maturidade representa um desenvolvimento na capacidade de previsão, no controle dos processos, na efetividade e na eficiência [20]. O entendimento de seus níveis de maturidade, permite à organização avaliar quais são suas forças e fraquezas, priorizando oportunidades de melhoria e melhor gerenciamento de planos de desenvolvimento [26].

As empresas mais orientadas ao desenvolvimento dos seus processos atingem níveis melhores de desempenho organizacional e conseguem criar um melhor ambiente de trabalho, baseado na cooperação e com menor número de conflitos [27]. Além de trazer benefícios internos, quanto maior é o nível de maturidade alcançado

por uma entidade, mais diversificada pode ser a sua base de clientes, tornando sua cadeia de suprimentos mais especializada [28].

Atributos

O modelo de maturidade é dividido em dimensões a serem analisadas. Dentro dessas dimensões, analisa-se individualmente alguns atributos, que possuem características e definições próprias [29] e são divididos nos níveis determinados pelo modelo de maturidade. Em um estudo que se referia ao CMM, citou-se que "se espera que os atributos [essenciais] caracterizem uma organização em um nível de maturidade específico" [30].

Os atributos detalham o modelo de maturidade, de forma a decompor certos aspectos de seu domínio [31] e, além disso, os atributos são utilizados para classificar um objeto de competência de uma das áreas empregadas no modelo de maturidade e podem ser atributos genéricos e atributos específicos. Os genéricos são aqueles comuns a todas as dimensões selecionadas no modelo (ELENA), enquanto os específicos são parte de apenas uma dimensão [32].

Em seu estudo acerca do desenvolvimento de um modelo de maturidade para implementação das tecnologias da Indústria 4.0, [33] definiram 7 dimensões e 38 atributos. Um exemplo de dimensão utilizada foi "Base tecnológica da Indústria 4.0", a qual avaliou mais especificamente 8 propriedades, dentre as quais tem-se Internet das Coisas e Internet de Serviços. Essas propriedades que são estudadas mais detalhadamente são conhecidas como atributos.

No que se trata do quesito dimensões de maturidade da cadeia de suprimentos, tanto a literatura quanto a prática sugerem que as principais categorias são planejamento, abastecimento, produção, entrega de resultados, desenvolvimento de novos produtos e itens que retornam à produção [19]. Do mesmo modo em que as dimensões evoluem ao longo do tempo, o nível de integração e desempenho de gestão da cadeia de suprimentos aumenta. Existem também algumas dimensões que se repetem em diferentes modelos, às vezes apenas com uma outra nomenclatura, mas com o mesmo significado [34].

Assim, os atributos mais frequentes presentes nos modelos selecionados na literatura foram: Flexibilidade; Tecnologia da Informação; Performance; Relação com o cliente; Inventário e Sistemas de Produção, conforme pode ser visto no Quadro 3.

Quadro 3. Relação dos atributos estudados nos modelos de maturidade selecionados na literatura

Atributos avaliados	Número de referência dos artigos selecionados										Σ
	[17]	[36]	[37]	[38]	[21]	[39]	[35]	[40]	[41]	[20]	
Relacionamento com o consumidor		x		x	x	x				x	5
Economia / custos			x						x		2
Flexibilidade	x		x		x	x	x			x	6
Recursos humanos		x			x	x					3
Busca pelo progresso								x	x	x	3
Tecnologia da informação		x		x	x	x	x	x			6
Estoque / inventário	x	x			x	x					4
Tempo de espera	x										1
Liderança					x			x	x		3
Gestão e Logística		x					x		x		3
Cultura da Organização					x		x				2
Performance	x	x		x		x	x			x	6
Planejamento e Estratégia				x	x		x				3
Sistemas de Produção		x				x		x		x	4
Produtos					x						1
Qualidade			x								1
Fornecedores				x		x					2
Trabalho em equipe								x			1

Após análise do Quadro 3, conclui-se que são poucos os autores que avaliam a tecnologia da informação ou algum outro aspecto ligado às tecnologias da Indústria 4.0, o que corrobora o desenvolvimento de um modelo que tenha seu foco voltado a esse aspecto.

A respeito da flexibilidade, em muitos periódicos esse é um atributo considerado importante na área de gestão operacional da cadeia. Por esse motivo, seu conceito já foi utilizado para diferentes objetivos, tais como medir a flexibilidade de produtos, de mix, volume e entregas. Neste caso, considerando as características das tecnologias 4.0, bem como as características dos consumidores atuais, é importante focar em um

outro conceito, que é a flexibilidade como medida da habilidade ou facilidade com que a cadeia pode mudar ou reagir à mudanças [35].

Sobre tecnologia da informação, busca-se medir a existência de ferramentas, métodos e dados que possam dar suporte aos sistemas da cadeia de suprimentos, por exemplo, dados estatísticos para previsão de demanda. A performance está voltada para a existência e a extensão de indicadores e medidores de desempenho da cadeia de suprimentos. Em termos de relação com o cliente, o que se avalia é o foco dado ao cliente como parte do processo de gestão da cadeia, além do nível de satisfação do cliente [34].

A dimensão relacionada ao gerenciamento do armazém ou inventário inclui todas as operações ligadas ao controle e gerenciamento de estoque, tais como matéria-prima utilizada, produtos acabados, peças de reposição, produção parada, etc. Por fim, os sistemas de produção representam todas as funções, processos e atividades que atuam diretamente na transformação de um produto ou serviço, ou seja, são as ações que agregam valor ao produto, como redução de defeitos, logística de problemas dentro da linha, planejamento de produção, bem como o desenvolvimento de projetos para redução de custo e tempo [36].

3 Modelo de Maturidade com foco na Indústria 4.0

Para o desenvolvimento do modelo de maturidade, primeiramente foram estudados os atributos mais frequentes na literatura. Conforme Quadro 3, apresentado anteriormente, os atributos de maior frequência foram: Flexibilidade; Tecnologia da Informação; Performance; Relação com o cliente; Inventário e Sistemas de Produção. Assim, pode-se considerar que estes atributos são os mais relevantes para a cadeia de suprimentos. A partir dessa relação, decidiu-se que uma das dimensões que iríamos adotar seria a Flexibilidade, justamente por ela ter sido considerada relevante por grande parte dos autores pesquisados. Em seguida, em função da alta frequência nos artigos e também por ser um dos focos deste estudo, decidiu-se que Produção seria nossa segunda dimensão analisada.

Além disso, ao longo da pesquisa percebeu-se que muitos autores consideravam a logística como ponto importante para estudo da cadeia de suprimentos. Sendo assim, e pelo fato de nosso foco ser também a Indústria 4.0, decidiu-se que uma das dimensões do modelo deveria incluir a logística, porém ligada a Indústria 4.0, resultando na dimensão de Logística 4.0. Por fim, é importante considerar que, apesar de não estar presente nos modelos de maturidade analisados, a sustentabilidade é um aspecto importante a ser considerado, pois possui uma força considerável para o gerenciamento das cadeias de suprimentos por parte dos líderes das empresas [42]. Portanto, o modelo proposto é composto pelos seguintes aspectos: Flexibilidade, Produção, Logística 4.0 e Sustentabilidade como dimensões principais. Em seguida, nos aprofundamos em cada uma dessas dimensões, dividindo-as em três atributos cada.

Por fim, baseando-se na relação de nome e número dos níveis de maturidade encontrados na literatura, apesar de a maioria dos autores adotarem uma divisão em 5

níveis, optou-se por utilizar quatro níveis, a fim de facilitar a compreensão da evolução da maturidade, por parte dos respondentes. Por fim, um questionário foi desenvolvido para avaliar e indicar o nível de maturidade da organização respondente, considerando os quatro níveis estabelecidos, e assim, indicar onde seus recursos deveriam ser investidos, a fim de otimizar o desempenho de sua cadeia em geral.

4 Considerações Finais

Como visto, a literatura já possui trabalhos feitos dentro da área nos quais apresentam alguns modelos que permitem a avaliação das cadeias de suprimentos. A partir dos atributos considerados mais relevantes e que aparecem em maior quantidade nos estudos realizados, é possível realizar a criação de um modelo de maturidade cada vez mais efetivo, de acordo com as mudanças no cenário logístico e industrial que contribuem para a evolução e melhoria das dimensões de cada cadeia de suprimentos. Com o aumento dos desafios na cadeia de suprimentos, as empresas devem tornar-se mais inteligentes para que saibam lidar com os novos problemas de gerenciamento [7].

Contudo, ainda há um déficit na construção de modelos que avaliem, de fato, o grau de maturidade inserido dentro do contexto da Indústria 4.0. Devido à recente implementação do termo, os estudos dentro da área ainda são muito básicos, o que impede um aprofundamento dos modelos de maturidade com enfoque neste tema.

Como há uma escassez de modelos que conectem os modelos de maturidade com a Indústria 4.0, paralelamente à esse estudo está sendo desenvolvido outro artigo, em que no modelo de maturidade desenvolvido serão adicionadas as tecnologias da Indústria 4.0, para avaliar a possibilidade de sugerir à empresa ou indústria uma ferramenta ou metodologia que possa auxiliar no desenvolvimento e na otimização dos processos que foram classificados com níveis mais baixos anteriormente. Além disso, o modelo de maturidade será testado pela primeira vez em uma indústria do setor automotivo, assim sendo possível avaliar tanto a efetividade do modelo quanto sua aplicação.

Como o conhecimento acerca das tecnologias digitais encontra-se cada vez mais difundido dentro das organizações, para trabalhos futuros vê-se a necessidade em de maior estudo dentro da correlação entre a Indústria 4.0 e os modelos de maturidade.

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Estudio de capacidad de producción en sistemas de producción de calzado basado en simulación

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Abstract. En este trabajo se aborda un caso de estudio de la industria manufacturera del calzado. Particularmente, se analiza el caso de una PyME de calzado de cuero de Argentina. El estudio se focaliza en la variabilidad de rendimiento que implica trabajar con materias primas de origen animal, y su consiguiente impacto en la capacidad de producción. Para ello se modeló el proceso de producción respetando todos los factores que incorporaban incertidumbre al problema. Se generaron simulaciones de eventos discretos para analizar el sistema, y se detectó el cuello de botella. Al analizar las potenciales alternativas para salvar la limitación en la capacidad, se optó por la incorporación de un nuevo trabajador. Los resultados de la propuesta de solución permitieron mostrar que incorporar un trabajador aumentaba la productividad más que proporcionalmente al incremento directo de mano de obra.

Keywords: Plant Simulation, planificación estocástica de la producción, producción de calzado, simulación, cuello de botella.

1 Introducción

La fabricación de calzado es una de las actividades productivas más importantes de Coronel Suárez, localidad de la Provincia de Buenos Aires, Argentina. Consiste en un proceso productivo de elevada complejidad, que involucra diversas máquinas específicas y una gran cantidad de operarios especializados. La diversidad de productos que se pueden obtener conlleva la necesidad de planificación de distintos procedimientos particulares, con operaciones adecuadas para cada modelo. Asimismo, en términos generales, la fabricación involucra las siguientes etapas: recepción de materia prima y cortado, aparado, armado y empaque.

El caso a trabajar es un problema de producción de calzado de seguridad de una empresa argentina, cuyos principales clientes son las fuerzas de seguridad. La problemática primordial radica en la necesidad de trabajar con cuero natural. Este material de origen animal se considera el insumo crítico del proceso puesto que interviene en mayor proporción en la fabricación del producto y, por sus características naturales, los rendimientos de su utilización no son constantes a causa de la variabilidad del tamaño de la pieza de cuero y a la elevada probabilidad de presencia de agujeros en la misma. Por lo tanto, las operaciones iniciales de todo el proceso de fabricación, es decir, el proceso

de cortado y preparado del cuero, tienen un rendimiento variable dependiente de las condiciones del cuero que ingrese. Además, dadas las características mecánicas del cuero, la operación de costura se vuelve realmente crítica. Por lo tanto, la probabilidad de ocurrencia de fallas (ej., rotura de agujas) u operaciones defectuosas (ej., costura deficiente) es significativa. La ocurrencia de dichos eventos (cueros no estándares y fallas operativas) impacta de forma negativa en la planificación de la producción.

En la literatura se encuentran numerosos antecedentes de trabajos que se basan en la simulación de eventos discretos para el estudio de casos similares de manufactura. Entre ellos, Malega et al. [1], Yang et al. [2], Zhang et al. [3] y Wang et al. [4]. Respecto a la industria del calzado, su estudio ha sido abordado por Dang & Pham [5], donde se realiza el diseño de una línea de montaje con 62 tareas, tiempos de operación inciertos y estaciones de trabajo paralelas, con el objetivo de maximizar el desempeño de la línea determinando un ajuste optimizado de los parámetros operativos y una asignación óptima de tareas. Por otra parte, Sadegui et al. [6] realiza la optimización de la línea de producción, haciendo foco en el área de costura, identificada como el cuello de botella del proceso. El objetivo es equilibrar la línea de montaje, minimizando el número de estaciones de trabajo requeridas y suavizando la carga de trabajo en los operadores.

Por otra parte, existen diversos casos donde se aborda la simulación de las fallas de equipos. Ahmadi et al. [7] evalúa las averías de máquina en un entorno estocástico mediante simulación, considerando que tiempo medio entre fallas y la reparación siguen una distribución exponencial. Las mismas consideraciones de distribución son utilizadas por Zandieh & Gholami [8].

En este trabajo se plantea el abordaje de un caso de estudio de una planta de producción de calzado de cuero. El proceso productivo está sujeto a distintas fuentes de incertidumbre que afectan la capacidad de producción, tanto por el rendimiento del cuero como por la probabilidad de rotura de las máquinas. Es por eso que, para aumentar la capacidad de producción, es necesario un abordaje que permita analizar la producción considerando las incertidumbres propias del proceso. Dada la cantidad de operaciones, la complejidad del proceso y la naturaleza propia del mismo (influencia significativa de factores aleatorios), resulta adecuado un enfoque basado en simulación de eventos discretos [9]. Se plantea como alternativa para el aumento de la capacidad de producción la incorporación de un nuevo trabajador. Los resultados avalan la alternativa propuesta mejorando la productividad más que proporcionalmente.

El resto del trabajo se organiza de la siguiente manera. En la Sección 2 se presenta el problema junto con el proceso productivo. En la Sección 3, se analiza la propuesta de mejora y se introduce la herramienta a utilizar. Mientras que en la Sección 4, se define el tipo de experimento a realizar junto con sus parametrizaciones, y se presentan los resultados obtenidos. En la Sección 5, se presentan las conclusiones del trabajo.

2 Descripción del problema

En esta sección, en primer lugar, se describe el proceso de fabricación completo del producto, desde la recepción de la materia prima hasta el acordonado y empaque del mismo. Posteriormente, se identifica y detalla el problema a resolver en este trabajo.

2.1 Descripción del proceso de manufactura

El borcego de seguridad es un producto hecho a base de cuero natural, forrado internamente y reforzado adecuadamente, provisto con suelas con propiedades dieléctricas, resistentes a óleos e hidrocarburos, cementada y pegada con costura de seguridad en Scátola.

El proceso de fabricación del producto en análisis se representa en el diagrama de flujo de la Fig. 1. Si bien el proceso real consiste en múltiples etapas específicas, para los fines del problema que se pretende estudiar en este trabajo se condensó dicha información. Esta condensación consistió en el agrupamiento de operaciones por centro de trabajo, manteniendo el suficiente nivel de detalle como para representar fielmente el problema de capacidad a trabajar. A su vez, esta condensación también respetó la naturaleza estocástica del problema, permitiendo modelar la variabilidad propia de trabajar con materias primas naturales (el rendimiento del cuero es variable) y su procesamiento exigente (rotura de máquinas). Por lo tanto, el problema modelado permite modelar el sistema real de producción validando el modelo.

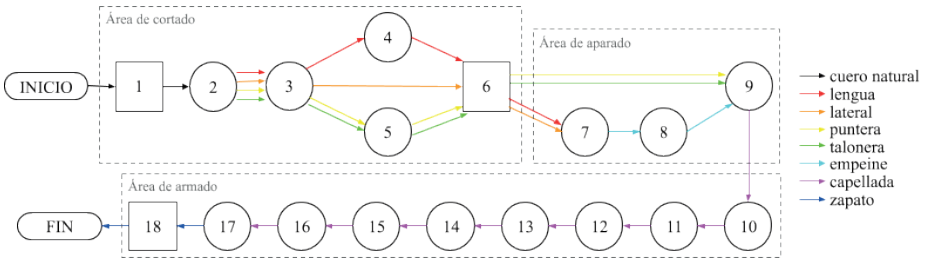

Fig. 1. Diagrama de flujo del proceso productivo de los borcegos de seguridad. Referencias: 1-Recepción de materia prima; 2-Cortado; 3-Rebajado; 4-Bordado de logo; 5-Pegado de refuerzos; 6-Control de calidad intermedio; 7-Cosido de lengua y laterales; 8-Ojalillado; 9-Cosido de la capellada; 10-Costura Strobel; 11-Humectado; 12-Calzado de horma y marcado; 13-Raspado, halogenado y cementado de suela y cortes; 14-Horno; 15-Pegado de suela; 16-Prensado de suela; 17-Costura de seguridad Scátola; 18-Control final, limpieza y empaque.

Su elaboración se inicia con la recepción de materia prima (1), a la cual se procede a realizarle la inspección táctil y visual del cuero, y el control y calibración de espesores. Los materiales se transportan al área de corte, donde se obtienen las diez piezas requeridas para la producción de un par de zapatos: 4 laterales, 2 lenguas, 2 punteras y 2 taloneras. Esto se realiza en un balancín pluma (2), junto con troqueles o sacabocados especiales para cada parte y a la medida de la horma del pie, con cuidado de descartar las secciones del cuero agujereado, arrugado o de espesor variable. Es importante que

se le realice un rebajado de cuero (3) de forma tal que disminuya el espesor en el perímetro de las piezas cortadas para que, al momento de realizar la costura entre piezas, se obtenga un espesor constante y se evite, además, la rotura excesiva de las agujas de las máquinas de coser. Posteriormente, se procede al bordado de la marca de los borcegos (4) en la lengua de éstos, el pegado de refuerzos (5) en las punteras y taloneras, y el control de calidad intermedio (6) de todos los componentes.

En el área de aparado se pegan, doblan y arman las distintas piezas del zapato. Los operarios se encargan de culminar la realización de la capellada realizando el ensamble de las piezas mediante su costura, utilizando máquinas de coser de una (9) y dos agujas (7). Adicionalmente, se realizan los ojales (8) requerido para el acordonado del zapato.

Luego, en el área de armado, se procede a la finalización del zapato. Esto requiere, en primer lugar, del proceso de montado, donde se cose la plantilla de armado mediante la máquina Strobel (10) y se trata el cuero con vapor (11) para ablandarlo en la máquina de humectar cortes. Posteriormente, se realiza el ensuelado por proceso de pegado tradicional, que consiste en el calzado de la horma y marcado de la suela (12), junto con su raspado, se incorpora el adhesivo y se pega (13). Para ello se incrementa la temperatura en un horno (14) y se pega a presión la suela durante 30 segundos (15 y 16). Por último, se desmonta la horma. Adicionalmente se realiza una costura de seguridad en Scátola (17).

Finalmente, el producto se limpia y se realiza el control final del mismo, procediendo a su acordonado y empaque (18).

En la Tabla 1 se muestra la cantidad de trabajadores que actualmente trabajan en la fábrica y el detalle de actividades que realiza cada uno. El número de operación coincide con las operaciones del diagrama de flujo presentado en la Fig. 1.

Tabla 1. Asignación de las operaciones productivas de los trabajadores. Las operaciones se definen a partir de las referencias del diagrama de flujo. Los trabajadores que realizan transporte manual de piezas se indican con una X en la última columna.

Trabajador	Cantidad	Operaciones	Transporte manual de piezas
Worker:1	1	(2)	
Worker:2	1	(3); (4)	X
Worker:3	1	(5); (6)	
Worker:4	1	(7); (8)	
Worker:5	1	(9); (10); (11)	X
Worker:6	1	(12)	
Worker:7	1	(13)	
Worker:8	1	(14); (15)	
Worker:9	1	(16)	
Worker:10	1	(17); (18)	X

2.2 Detalle del problema a resolver

La problemática principal de este proceso es que, al trabajar con materias primas naturales, su acondicionamiento exige un procesamiento intensivo, el cual termina limitando la capacidad de producción real de la planta. Esta limitación se da en el proceso de fabricación por la gran variabilidad del rendimiento de la principal materia prima que es el cuero natural. Al tratarse de un insumo de origen animal, no solo el tamaño de las piezas recibidas resulta variable, sino que también puede presentar agujeros, o algunas secciones quemadas (por el proceso de curtiembre) y con gran frecuencia el espesor es variable. Para minimizar el impacto de estas condiciones en el proceso de producción, la elección del proveedor de materia prima es fundamental, al igual que las habilidades del cortador (operación 2, Fig. 1), quien debe posicionar los troqueles de tal forma que se minimice el descarte de piezas cortadas no aptas para lograr el nivel de calidad deseado del producto final.

Sin embargo, una vez logradas las piezas cortadas, la mayor exigencia se encuentra en el área de aparado (operaciones 7,8 y 9, Fig. 1), donde los operarios deben calibrar las máquinas de coser según el espesor del cuero, ya que, si no se ajusta la máquina al espesor del cuero, entonces la probabilidad de rotura de las agujas crece considerablemente. Es por eso que el desempeño del área de aparado tiene una vinculación directa con el cuero. La criticidad del ajuste de máquina al espesor del cuero es tal que, en una jornada estándar de trabajo, se pueden llegar a romper 10 agujas por día (realizando todos los ajustes necesarios) y, en caso de saltear algún ajuste, la cantidad de roturas de agujas aumenta. Por lo tanto, es un área que demanda mucho tiempo de setup (no es tiempo productivo), e incluso el tiempo de reparación por rotura también es considerable.

Por otro lado, las operaciones de costura allí realizadas inciden directamente en la calidad y estética de los borcegos terminados, por lo que un mal desempeño genera una obtención mayor de zapatos de segunda calidad, lo cual tiene un impacto económico para la empresa. Por lo tanto, se trata de una operación que debe realizarse con el máximo de los recaudos, lo que en términos operativos implica tiempos de operación no reducidos. Es por eso que, para aumentar la capacidad de producción, debe analizarse detenidamente el área de aparado. Para ello se realizaron una serie de simulaciones en condiciones estándares para evaluar, en términos relativos, como se desempeñaba dicha área. En la Fig. 2 se presenta una gráfica que muestra la utilización del tiempo de la jornada laboral por parte de cada trabajador (del inglés, "*worker*"). A simple vista se observa que el único trabajador sin tiempo ocioso es el trabajador 4 (la parte verde implica modo "operación" y la parte gris "esperando"), que resulta ser el trabajador asignado a las operaciones (7) y (8) (Tabla 1). Por lo tanto, se identifica que la limitante de capacidad o el cuello de botella se encuentra en las operaciones (7) y (8) asignadas al trabajador 4.



Fig. 2. Gráfico de barra de las proporciones de los tiempos de las distintas actividades realizadas por cada operario en función del tiempo total de trabajo normalizado, bajo condiciones iniciales.

3 Propuesta de solución

En esta sección se parte del proceso de producción presentado, junto con sus características estocásticas, para analizar una potencial alternativa que permita aumentar la capacidad de producción. Para ello primero se describe la propuesta de solución en términos del proceso productivo y, luego, se proponen los medios para evaluar la solución propuesta.

3.1 Propuesta de solución

El problema de capacidad se evidencia en las operaciones (7) y (8) que son las que realiza el trabajador 4. Esas limitaciones de capacidad se deben a que es una operación muy demandante de mano de obra debido al permanente ajuste que debe realizarse en la máquina para procesar el cuero de espesor variable. Por lo tanto, para aumentar la capacidad de producción del sistema, bastaría con aumentar la capacidad del cuello de botella [10]. Ahora bien, una forma de aumentar la capacidad de producción de esas operaciones sería reduciendo la cantidad de tiempos de ajustes que requiere esa máquina, ya que éstos no son tiempos productivos en el sentido estricto. Sin embargo, la necesidad de los ajustes de máquina se debe a la variabilidad del espesor del cuero, que, tal como se comentó en la sección anterior, es una característica propia de la materia prima que se utiliza para el proceso. Por lo tanto, para reducir el tiempo destinado a los ajustes, sería necesario reducir la variabilidad del espesor del cuero, algo que no es posible.

Por lo tanto, la posibilidad de aumentar la capacidad de esas operaciones radica en aumentar los recursos productivos disponibles en esa operación, ya sea aumentando la cantidad de máquinas, o aumentando la cantidad de operarios. En este trabajo optamos por esta última opción. Lo que se propone como solución para el aumento de la capacidad de producción es la incorporación de un nuevo trabajador asignado a las mismas operaciones que el operario 4 de la Tabla 1.

3.2 Enfoque de implementación de la solución

Para la verificación de la efectividad de la alternativa elegida para el aumento de la capacidad, se utiliza el software Tecnomatix Plant Simulation 15 [11]. Se trata de un

software de simulación del flujo de material en un sistema de eventos discretos. El software permite evaluar procesos complejos y dinámicos brindando el soporte a la toma de decisiones relacionadas con la producción. Para ello, el simulador permite la ejecución de distintos experimentos representando distintas alternativas y configuraciones, sin requerir la experimentación con el ambiente real de producción.

Para el modelado del proceso productivo se tomó en consideración el layout real de la empresa, con tiempos estimados a partir de la producción diaria promedio. Ese Layout se presenta en la Fig. 3., los números asociados a cada una de las estaciones de trabajo condice con los números presentados en las etapas del proceso de la Fig. 1.

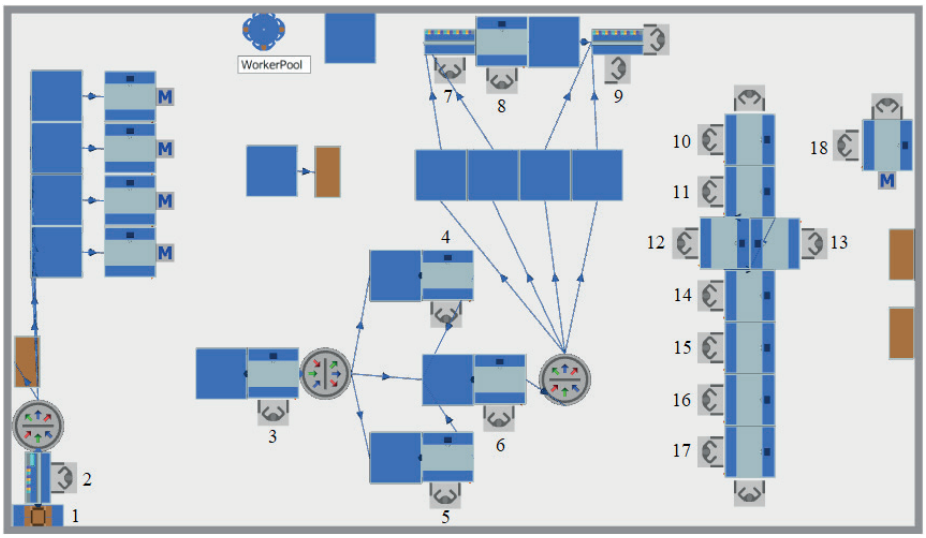

Fig. 3. Vista en planta del modelo 3D del proceso productivo real de calzado, utilizando Plant Simulation. Las referencias corresponden a las operaciones del diagrama de flujo de la Fig.1.

4 Experimentos y resultados

4.1 Diseño experimental

La realización de los experimentos requiere un modelado previo del sistema productivo. Se introdujeron diversos puntos de variabilidad asociados al rendimiento de la materia prima, los tiempos de operación, las fallas operativas por rotura de agujas en el área de aparado y la calidad del producto terminado.

En el caso del rendimiento del cuero natural, se definió considerando un proveedor de materia prima de calidad media-alta, donde las piezas descartadas debido a las deficiencias del material varían de 0 a 4%, con una distribución uniforme.

Respecto a los tiempos operativos, éstos fueron estimados a partir de la información del caso real provista por la PyME, tomando en consideración la producción diaria de

100 zapatos/día. Dado que las actividades son realizadas con la intervención de los trabajadores, los tiempos pueden discrepar debido a factores inherentes del sistema. Dicha variabilidad se modela a partir de una distribución triangular de los tiempos operativos, considerando a los valores mínimos y máximos como una proporción equivalente al 95% y 115% del valor de la moda, respectivamente.

Las fallas por rotura de agujas de las máquinas de coser del área de aparado se determinan a partir de la rotura histórica de agujas en la totalidad de la fábrica, que dependen del material que se procesa. Para el caso particular del cuero, debido a sus características, la rotura es de aproximadamente 10 agujas/día y, se definió para ambas máquinas con un intervalo entre roturas caracterizado por una distribución exponencial negativa. Por su parte, la duración se define a partir de una distribución normal, con un valor esperado de 4 minutos y una desviación estándar de 15 segundos.

Finalmente, se modeló la variabilidad del control de calidad final (operación 18 de la Fig. 1) de manera análoga al rendimiento del cuero. En este caso, los zapatos catalogados como de segunda calidad son de 0% a 2% de la producción total, con una distribución uniforme.

Por último, se establece para la jornada laboral la realización de un único turno, de lunes a viernes, desde las 6:00 hasta las 15:30 hs., con un descanso de 1 hora. Las condiciones hasta aquí detalladas se mantienen durante la realización de los experimentos. Como se describió previamente, la alternativa que se evalúa es incrementar la capacidad del sistema actuando sobre el cuello de botella, lo cual implica la incorporación de un nuevo operario con condiciones idénticas al trabajador 4. Por lo que los experimentos analizados consistieron en:

- Experimento 1: configuración estándar y cantidad de trabajadores estándar
- Experimento 2: configuración estándar y cantidad de trabajadores +1.

4.2 Resultados

Para comparar los dos experimentos se consideró como métrica de comparación la productividad promedio diaria. Se realizaron 50 corridas de cada experimento, con una extensión de 30 días. Los resultados obtenidos se muestran en la Fig. 4 a través de los intervalos de confianza. En la Fig. 4 se observan mejoras sustanciales en la productividad al incorporar un operario más (Experimento 2). El mayor impacto se da en las salidas de borcegos terminados. Bajo las condiciones iniciales (Experimento 1), la producción media es de 2786,73 pares/mes, con un desvío estándar de 286,04 pares. Al implementar la segunda estrategia, incorporando únicamente un nuevo operario en el cuello de botella, la producción es de 3562,47 pares/mes, con un desvío estándar de 340,63 pares. Es decir, la productividad se ve incrementada en un 27,84%. Este incremento porcentual si se lo compara con el incremento porcentual de la fuerza de trabajo (1 trabajador sobre 10 trabajadores, 10%) implica un aumento más que proporcional.

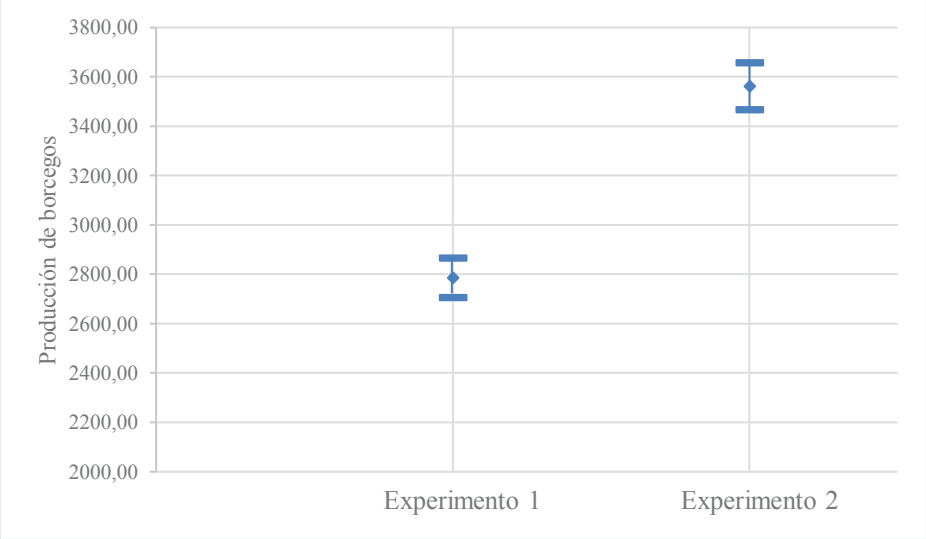

Fig. 4. Intervalo de confianza de la producción de borcegos para el experimento 1, con las conficiones iniciales, y el experimento 2, con la capacidad del cuello de botella incrementada.

Por otra parte, al observar la distribución de la proporción del tiempo trabajado por cada operario (Fig. 5), se observa un incremento general y una disminución en los tiempos de espera, comparado con la Fig. 2. Es de interés consignar que el nuevo trabajador incorporado es denominado como "Worker 5" en la Fig. 5, por lo que los Worker 6 a 11 de la Fig. 5, corresponden a los Worker 5 al 10 de la Fig. 2. Por otro lado, se observa en la Fig. 5, que la carga de trabajo se encuentra más balanceada entre los distintos trabajadores del proceso (las barras verdes tienden a ser más equilibradas que en la Fig. 2).



Fig. 5. Gráfico de barra de las proporciones de los tiempos de las distintas actividades realizadas por cada operario en función del tiempo total de trabajo normalizado, para el Experimento 2. El trabajador adicional se encuentra referenciado como Worker:5, por lo cual los demás trabajadores se ubican desfasados de su designación previa de la Fig. 2.

5 Conclusiones

El trabajo abordó la resolución de la problemática de capacidad de un caso real de una línea de producción de calzado. Para esto, se realizó un modelo de simulación del proceso productivo utilizando el software Plant Simulation, que permitió detectar la principal restricción del sistema, a saber, el área de calzado, en particular el trabajador 4. En consecuencia, se planteó una solución alternativa para incrementar la capacidad del cuello de botella añadiendo un operario extra, y se llevaron a cabo experimentos para evaluar el impacto de la solución propuesta.

Los resultados obtenidos a partir de la comparación de la situación inicial y la alternativa reflejan un impacto positivo significativo en la producción mensual de borcegos de la fábrica. Es decir, la solución propuesta potencia el sistema en conjunto, de forma más que proporcional al incremento de la capacidad.

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Medição de desempenho baseado em dados para máquinas: Revisão sistemática de literatura

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Resumo: A indústria 4.0 vem mudando a forma de produzir, oferecendo tecnologias inteligentes aos sistemas de manufatura para a transformação tecnológica das plantas fabris. Esta mudança depende de aplicações e combinações de tecnologias digitais como a (IoT) para o monitoramento *online* para a realização da coleta, do armazenamento e da transformação dos dados do processo em informações valiosas para auxiliar nas tomadas de decisões. Neste contexto, constatou-se, que as pequenas e médias indústrias apresentam dificuldades na utilização dos dados de processo e são apontadas como um elo fraco, tornando-se as maiores vítimas na transição para a indústria 4.0. A pesquisa apresenta como objetivo a avaliação de como estão sendo tratada a medição de desempenho baseada em dados para máquinas, no contexto da indústria 4.0. A abordagem metodológica segue por meio da aplicação do método (*Knowledge Development Process-Constructivist*) Proknow-C, para a construção do Portifólio Bibliográfico e da Análise Bibliométrica de forma estruturada alinhando ao tema de pesquisa. O resultado apresentou o método de seleção do Portfólio Bibliográfico e a Análise Bibliométrica para mensurar de forma qualitativa e quantitativa o grau de relevância e reconhecimento científico da seleção do Portfólio Bibliográfico, o qual possibilitou a análise dos dados para construção de um modelo de medição de desempenho com base nas fontes dos artigos pesquisados.

Palavras-chaves: Manufatura Conectada, Data Analytics, Medição de Desempenho, Manufatura Inteligente.

1. Introdução

As descobertas no campo da ciência e tecnologia vêm ocorrendo e progredindo através das revoluções industriais gerando inovações na computação e automação no processo produtivo [1]. Nestas evoluções, muitos dos dados, os quais podem ser utilizados para a medição do desempenho de máquina permanecem retidos nas máquinas e precisam ser extraídos e compilados manualmente para obter a informação de desempenho [2]. Recentemente a indústria de manufatura foi promovida para *Smart Manufacturing* (SM) e os processos advindos da indústria 4.0 vêm sendo altamente flexíveis, dependendo do desenvolvimento de inovações baseada em dados, para alcançar altos níveis de autonomia e otimização da manufatura [3, 4]. Um entendimento notável e comum, é que os sistemas de

manufatura evoluam para acomodar algumas características, tais como: A inteligência para a fabricação de objetos constituídos por homens, máquina e material (3M); A conexão para a configuração de objetos de fabricação, utilizando conexões com outros objetos do sistema para colaboração, conhecimento e serviços disponíveis na *internet;* e a capacidade de resposta por meio da fabricação (personalizada) lidando com mudanças internas e externas [4, 5].

Os conceitos trazidos pela indústria 4.0 são as principais prioridades para muitas organizações, entretanto o termo indústria 4.0, ainda não está claro para muita delas, segundo [6], algumas empresas enfrentam dificuldades para entender estes fenômenos e não obtém o conhecimento para identificar as etapas necessárias para uma transição saudável para alcançar a indústria 4.0. A IoT criado por Ashton, no Auto-ID Center do MIT em 1999, foca na formação de uma "*Internet*" composta por grandes números de "Coisas" interconectadas por uma infra-estrutura global de inter-rede que usa o protocolo TCP/IP para conectar e controlar remotamente as "Coisas" [3, 5]. Com a crescente demanda de IoT e dispositivos de sensores espera-se, que os dados gerados a partir de um processo de fabricação cresçam exponencialmente gerando os chamados "*big data analytics*" foco da *smart manufacturing,* oportunizando o desenvolvimento de um sistema para o monitoramento *online*, gerando informações para auxiliar os gestores nas tomadas de decisões [7, 6]. A *big data analytics* é um dos recentes avanços tecnológicos com forte aplicabilidade na manufatura [8]. A coleta, o armazenamento e a transformação de uma grande quantidade de dados são um dos principais elementos da manufatura inteligente industrial [7].

Para manter o alto desempenho dos sistemas de manufatura exige-se das indústrias, o emprego de métodos e ferramentas para gerenciar a medição do desempenho ao longo do ciclo de vida do sistema, os quais são introduzidos para garantir o desempenho planejado por meio do monitoramento *online*, avaliação do desempenho e resposta para adequação dos desvios do desempenho. A medição é seguida pela análise do desempenho por meio de indicadores, para que as decisões sejam tomadas. Nos níveis mais altos da fábrica, as medições de desempenho são agrupadas nos principais indicadores de desempenho *key performance indicators* (KPIs). O KPI é um parâmetro e fornece informações sobre um fenômeno com significado e relevância para os objetivos de desempenho, como um fator crítico para o sucesso atual e futuro da organização e devem ser numericamente e precisamente quantificáveis [9].

Para [9], a coleta e a análise otimizada destes dados, os quais auxiliam a gestão nas tomadas de decisões são, no entanto, um processo complexo e dinâmico. Isto é, ainda mais verdadeiro, nas pequenas e médias indústrias, as quais apresentam dificuldades em utilizar os dados do processo e foram classificadas como um elo fraco, sendo as maiores vítimas na transição para a indústria 4.0 [10]. A realidade descrita, sobre as dificuldades das pequenas e médias indústrias em adaptarem seus processos e recursos, para uma transição saudável para a indústria 4.0, revela uma problemática, a qual apresenta como fator determinante à baixa adoção de tecnologias para a medição de desempenho baseada em dados para máquinas. Diante desta problemática, qual

alternativa poderia ser proposta para a medição do desempenho para máquinas e equipamentos de forma *online*, e desta forma contribuir para mitigar os impactos na transição para a indústria 4.0? Para tanto, o objetivo geral da pesquisa foca na avaliação de como estão sendo tratada a questão da medição de desempenho baseada em dados para máquinas no contexto da indústria 4.0.

2. Procedimentos metodológicos

Para o desenvolvimento desta pesquisa, foram aplicadas duas, das 4 etapas da metodologia *Proknow-C*, sendo a seleção de um portfólio e a análise bibliométrica do portfólio. Desta forma, será construída apenas parte do conhecimento, os quais são suficientes para identificar o modelo de avaliação acerca do tema da pesquisa conforme (Fig.1)

2.1 Metodologia de pesquisa: Proknow-C

O *Knowledge Development Process-Constructivist (Proknow-C)* é um método de revisão sistemática proposto por [11, 12], similar aos demais e destaca-se no propósito da geração do conhecimento [32]. O método *Proknow-C* é utilizado tanto para a seleção de Portfólio Bibliográfico, quanto para Análise Bibliométrica de forma estruturada e gradual alinhado ao tema de pesquisa. Partindo do pesquisador, o interesse para delimitar e definir as premissas, no que tange as bases de pesquisas, aos eixos de buscas, aos cortes temporais, aos filtros e aos critérios para inclusão ou exclusão de publicações [13, 14, 15, 16, 17, 32]. Permitindo a construção do conhecimento, dando suporte à realização das pesquisas na seleção de publicações considerando o fator de impacto relevante na comunidade científica [18, 19]. O método é composto por quatro etapas (Fig.1): (a) seleção de um portfólio bibliográfico; (b) análise bibliométrica do portfólio; (c) análise sistêmica; e, (d) definição da pergunta de pesquisa e objetivo de pesquisa [15, 16, 17, 20].

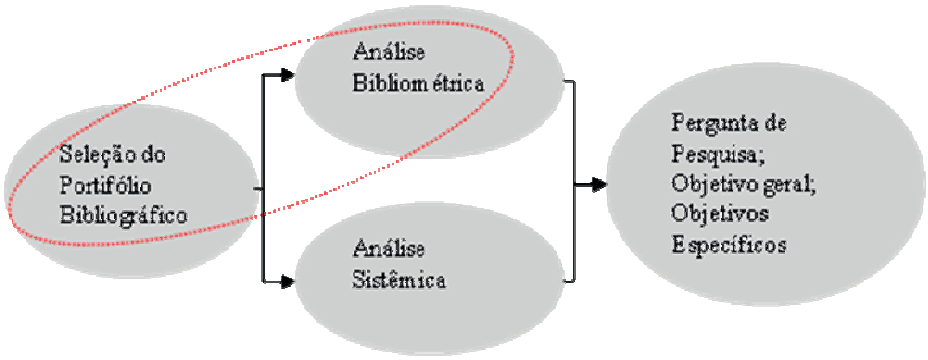

Fig.1. Etapas do processo Proknow-C. Adaptado de [12]

2.2 Seleção do Portfólio Bibliográfico

A busca pelas publicações científicas foram realizadas, nas bases de dados de forma sistemática, seguindo a metodologia *Proknow-C*. O processo de seleção de portifólio de artigo contribuiu para a seleção de Portfólio Bibliográfico, considerando como relevante na comunidade científica [21; 14]. De acordo com [15; 21] o subprocesso de seleção do portfólio são desenvolvidos através de duas etapas: a) a seleção dos artigos nas bases de dados (Banco de Artigos Brutos); e b) a filtragem dos artigos selecionados alinhado ao tema da pesquisa.

Etapa (a) iniciou-se com as definições de três eixos de pesquisa representadas pelos termos de buscas em língua inglesa: *manufacturing, data analytics and Performance measurement.* As buscam foram realizadas nas bases de pesquisa *(Scopus, ScienceDirect e Web of Science,* em Agosto de 2019, seguindo o critério de artigos publicados nos últimos seis anos (2013 a 2019) e validando-os com o teste de aderência dos termos de buscas. **Etapa (b)** em seguida foram aplicados os filtros, tais como: a exclusão de artigos com acesso restrito e em duplicidades, artigos com títulos e *abstracts* não alinhados ao tema de pesquisa. Resultando na construção de um Portfólio Bibliográfico, alinhados ao tema e reconhecidos na comunidade cientifica.

2.3 Análise Bibliométrica do Portfólio Bibliográfico

A fase de Análise Bibliométrica denominada por [15], caracteriza pela aplicação da análise dos artigos, para o gerenciamento da informação e do conhecimento científico para o pesquisador, sobre o tema pesquisado [13]. O objetivo desta análise foca na quantificação e apresentação destas informações, através de ferramentas de análises e construção deste conhecimento [14, 21]. Os resultados destas análises da fase de bibliometria foram desenvolvidos em quatro etapas, de acordo com [18, 19, 21, 22, 23, 24, 25]: (a) Estimar o grau de relevância dos periódicos; (b) Estimar o reconhecimento científico dos artigos; (c) Estimar o grau de relevância dos autores; (d) Estimar as palavras-chave mais utilizadas.

3. Análise de Resultados

3.1 Seleção do Portfólio Bibliográfico

O processo de seleção de portfólio consiste em selecionar publicações, consideradas relevantes na área de conhecimento e alinhadas com percepção do pesquisador ao tema de pesquisa. No entanto, o processo de seleção [21], segue em duas etapas: O item 3.1.1 refere-se à construção da base de seleção de artigos brutos e o item 3.1.2 consiste na filtragem da base bruta de artigos, com base no alinhamento do tema de pesquisa.

3.1.1 Seleção do banco de artigo brutos

a) Termo de busca: Inicialmente foram necessárias identificar os eixos da pesquisa, para posteriormente indexar em cada eixo, aos termos de buscas relacionadas com o tema de pesquisa. As combinações dos eixos com as palavras chaves seguem conforme Tabela 1, todas descritas no idioma inglês.

Tabela 1. Termo de buscas

Eixo I: *Manufacturing*	**Eixo II: *Data Analytics***	**Eixo III: *Performance measurement***
Smart production	*Internet of Things*	*Key performance Indicator (KPI)*
Industry 4.0	*Machine learning*	*Machine performance*
Smart manufacturing	*Real-time process*	*Productive efficiency monitoring*

b) Definição do banco de dados: Para a pesquisa foram selecionadas 3 bases de publicação cientifica, sendo elas: *Scopus, ScienceDirect e Web of Science*.

c) **Busca de artigos no banco de dados foram** realizadas nas bases dos periódicos definidas no item (b) em agosto de 2019, com filtro de datas para os artigos publicados entre os anos de 2013 a 2019, sendo selecionado para o banco de artigos brutos um total de 880 títulos relacionado ao tema de pesquisa, sendo 277 artigos pela *Scopus*, 378 pela *ScienceDirect* e 225 pela *Web of Science*.

d) Testes de aderência dos termos de buscam verificaram, se os termos inicialmente determinados na busca das publicações do Portfólio Bibliográfico, se alinham com o tema de pesquisa. O resultado evidenciou, que, dos 13 termos de buscas pertencentes aos dois artigos, sete deles *(smart manufacturing, manufacturing performance methods, manufacturing performance challenges, performance measurement, manufacturing, big data, real-time processing)* encontravam-se listados entre os termos de buscas definido nos eixos da pesquisa.

3.1.2 Filtragem do banco de dados

Esta etapa consiste na seleção dos artigos disponíveis com maior relação ao tema e o fator de impacto na comunidade científica. Para esta análise, a base de dados foi exportada para o *Software Mendeley* e as informações contidas como (título, *abstract*, palavras-chaves, autores, DOI entre outros, o arquivo em PDF da publicação). Na sequência, foram realizados os filtros, por meio de leitura, dos 880 artigos do banco de artigos brutos (BAB) para dar origem à base do Portfólio Bibliográfico.

a) Filtros dos artigos quanto à (repetição e redundância): Esta fase analisou por meio do *Software Mendeley,* o banco de artigos brutos, com 880 obras

selecionadas. Assim foi possível verificar a redundância dos artigos, sendo que, 21% (168) dos artigos foram removidos por apresentar duplicidade e acesso restrito, restando 698 artigos no banco de artigos brutos;

b) Filtros dos títulos dos artigos estão alinhados com o tema da pesquisa: Nesta fase foram realizadas as leituras integrais dos títulos dos 698 artigos da base de artigos brutos. Destes 82,5% (576) artigos foram excluídos, pois não estavam alinhados com o tema de pesquisa. No final desta etapa restaram na base de artigos brutos, apenas 11,6% (81) das obras selecionadas;

c) Filtros dos resumos dos artigos estão alinhados com o tema da pesquisa: Realizado mais um corte, desta vez, no que tange ao alinhamento do *abstract* com o tema de pesquisa. Dos 81 artigos filtrados na fase anterior, 72,8% (59) artigos foram removidos do portifólio, em função do *abstract* não estar alinhando com o tema de pesquisa. Restaram nesta fase 22 artigos.

d) Filtro de reconhecimento científico: Para verificação do reconhecimento científico dos 22 artigos, foram realizadas duas pesquisas: uma na base do *Google Scholar* para consultar os números de citações obtidas por cada artigo. Outra na base *Journal Citation Reports (JCR)*, para verificar, qual o fator de impacto científico dos periódicos indexados na Web of Science. Nesta fase, em relação às citações dos artigos na plataforma Google Scholar, apenas 4,5% (1) artigo não obteve nenhuma citação, mas foi considerado no portifólio por dois motivos: O primeiro por ser uma publicação de maio de 2019, e o segundo, por estar publicado no periódico com maior fator de impacto dentre as bases que compões o portifólio. Quanto o fator de impacto dos periódicos indexados na Web of Science, 27,2% (6) artigos foram eliminados por não obter o índice JCR, sendo 18% (4) foram publicados em congressos internacionais e 9% (2) foram publicados em revistas científicas internacionais. Restando 72,7% (16) para análise de alinhamento textual.

e) Filtro de alinhamento do texto integral com o tema de pesquisa: Ao final da seleção de portifólio 13 artigos foram relevantes e estão alinhados ao tema de pesquisa reconhecido cientificamente, tanto por citações das publicações, quanto pelo fator de impacto dos periódicos.

3.2 Análise Bibliométrica do Portfólio Bibliográfico

O processo de Análise Bibliográfica consiste na aplicação de métodos matemáticos e estatísticos [21]. Para [20], a análise bibliográfica foca em gerar conhecimento ao pesquisador sobre as características da pesquisa. Nesta etapa, [20] o pesquisador pode alcançar dados complementares sobre o tema de pesquisa e construir inferências para sustentar as suas escolhas. Sendo assim, [21] sugere o desenvolvimento da bibliometria em quatro etapas: 3.2.1 Estimar o grau de relevância dos periódicos;

3.2.2 Estimar o reconhecimento científico dos artigos; 3.2.3 Estimar o grau de relevância dos autores; 3.2.4 Estimar os termos de buscas mais utilizados.

3.2.1 Estimar o grau de relevância dos periódicos

Para estimar o grau de relevância do periódico foram consideradas duas análises: A **primeira** refere-se à identificação do periódico, que obteve o maior número de publicação. A análise evidenciou que os artigos do portifólio bibliográfico foram publicados em 12 periódicos. Deste portifólio, o "*International Journal of Production Research*" foi o que apresentou o maior grau de relevância, com duas publicações, os demais, apenas um cada. A **segunda análise** buscou-se avaliar o fator de impacto científico dos periódicos, onde os artigos do Portfólio Bibliográfico foram publicados. Esta análise seguiu por meio do JCR, uma ferramenta da Clarivate Analytics usada para avaliar e comparar periódicos. Para tanto, de acordo com a (Fig.2), segue, o *ranking* dos periódicos que compõe o Portfólio Bibliográfico. O *ranking* geral do JCR é composto por 12.515 posições e todos os 13 artigos do Portfólio Bibliográfico possuem relevância com impacto científico relevante indexado pelo (JCR). "A melhor classificação obtida foi pelo Periódico *"Technological Forecasting and Social Change"* na posição no *ranking* em 1784 com a publicação do artigo intitulado "*Influence of big data adoption on manufacturing companies' performance: An integrated DEMATEL-ANFIS approach"*. As demais classificações seguem na ordem de menor para maior posição do *ranking*.

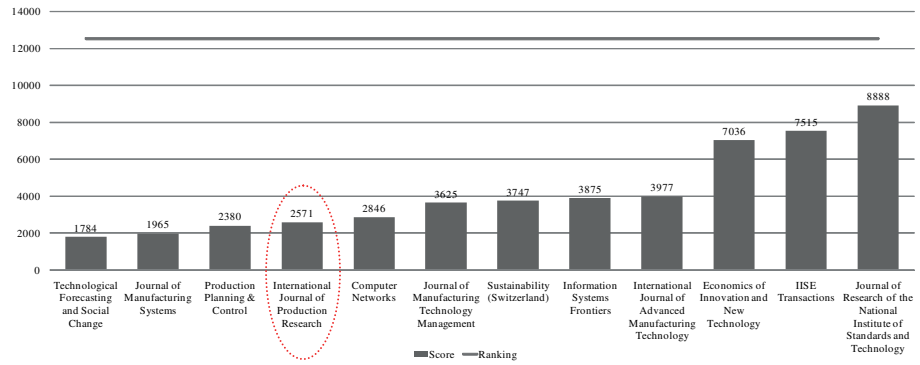

Fig.2. *Ranking* do Portfólio Bibliográfico. Adaptado de Journal Citation Reports (2019)

3.2.2 Estimar o reconhecimento científico dos artigos

O reconhecimento científico dos artigos do Portfólio Bibliográfico consiste em pesquisar a quantidade de vezes que o artigo foi citado, para isto utilizou-se como base de consulta, a plataforma *Google Scholar*. No contexto ilustrado pela (Fig.3), seguem os resultados. Todos os artigos apresentaram ao menos uma citação no indexador do Google Scholar. O artigo, que obteve o maior número de citação (127), está intitulado como "*Deep learning for smart manufacturing: Methods and*

applications publicado em (2018)". Vale considerar, que a data de publicação, no caso, publicações recentes apresentam menos citações, mas este fator, não reduz o grau de relevância do artigo, na pesquisa.

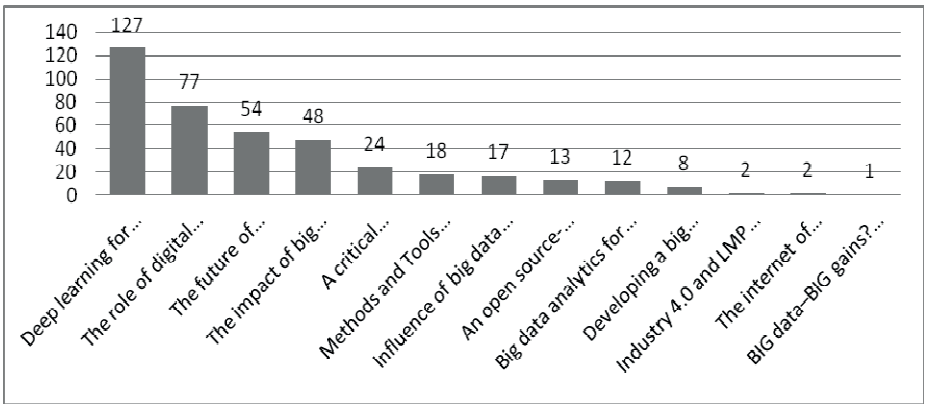

Fig.3. Citações dos artigos do Portfólio Bibliográfico. Adaptado de Google scholar (2019)

3.2.3 Estimar o grau de relevância dos autores

Nesta fase analisou-se por meio da plataforma Google Scholar o numero de vezes, que os autores foram citados em outras pesquisas. No total de 50 autores, 35 tiveram citações formalizadas e outros 15 não foram localizados na plataforma. A (Fig.4) apresenta os dez primeiros colocados citados em outras. As análises referem-se a somente a esta pesquisa.

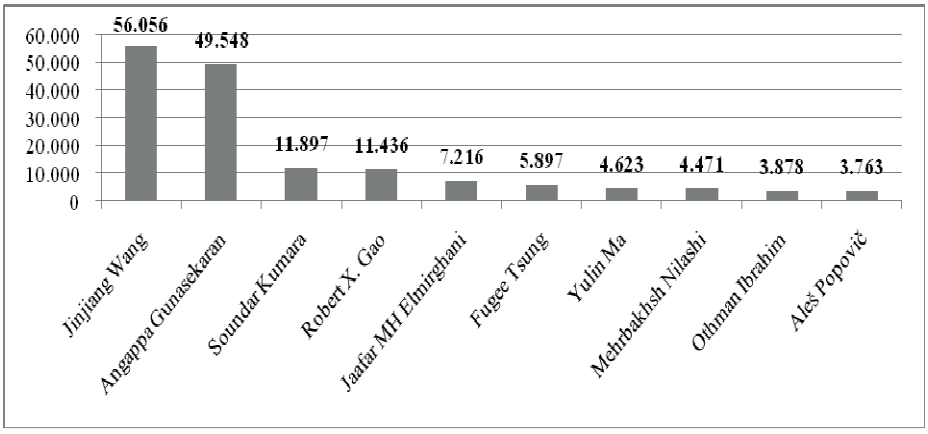

Fig.4. Citações dos 10 autores mais citadas em outras pesquisas. Adaptado de Google scholar (2019)

3.2.4 Estimar os termos de buscas mais utilizados

Neste caso, é interessante observar, através da (Fig.5), entre todos os 62 termos de buscas identificadas no Portfólio Bibliográfico, os 10 primeiros, correspondem a 55% dos que foram utilizadas nos eixos de busca da pesquisa.

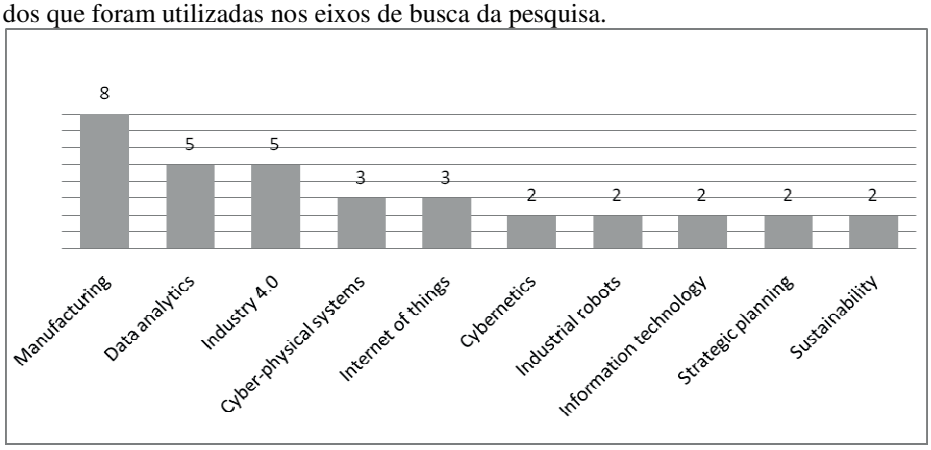

Fig.5. Relevância dos termos de buscas

3.3 Contribuições para o avanço da área

Sobre a avaliação de como esta sendo tratada a questão da medição de desempenho baseada em dados para máquinas, no contexto da indústria 4.0 percebeu-se, que o tema abordado, enfrenta grandes desafios, os quais vão desde a aplicação da pesquisa para o desenvolvimento para oferecer um roteiro estratégico, como guia para o processo de transição para a indústria 4.0 [6], até a avaliação de sucesso para a transformação das indústrias em fabricas inteligentes [26]. Evidenciou-se, nas literaturas pesquisadas dos últimos anos, que o tema incorpora outras dimensões sustentáveis na transformação digital [20]. Para [7, 9] estas dimensões podem auxiliar nas tomadas de decisões, no que tange a falta de conhecimento arquitetônico centrada na IoT, relacionada à grande quantidade de dados, com a dificuldade de coleta, armazenamento e análise deste volume de dados. A crescente ênfase na transformação digital está relacionada em apresentar um caminho para reduzir às limitações de recursos na revolução industrial 4.0, auxiliando a gestão das pequenas e médias indústrias, no processo de transformação digital [6]. Os resultados deste estudo podem ajudar a gestão destas pequenas e médias indústrias de manufatura, a focar com precisão nos fatores relevantes, para contribuir com os modelos de medição de máquinas baseada em dados para máquina, com as inovações tecnológicas, a fim de melhorar desempenho e competitividade futura de seus processos e estratégias [8]. A Tabela 2 apresenta uma lista de sugestões de pesquisas futuras inspiradas pelos autores, para o avanço e evolução da área identificada no Portfólio Bibliográfico.

Tabela 2. Relação das oportunidades identificada no Portfólio Bibliográfico

Aspectos de Avaliação	**Autores**	**Pesquisas Futuras**
Realização de pesquisas para a construção de um modelo	[6]	Identifica o melhor roteiro estratégico para a transição da indústria 4.0, na gestão das pequenas e médias empresas.
	[3]	Concentrar na aplicação de outras teorias para analisar a geração de conhecimento a partir dos dados gerados pelo monitoramento *online*; o retorno do investimento sobre as inovações tecnológicas em organizações, que estão muito longe da perspectiva operacional da indústria 4.0; realizar a aplicação e a implementação da estrutura proposta para analisar a integração do *Cyber Physical*.
	[7]	Investigar o *design* ideal da estrutura da arquitetura baseado em código aberto no processamento de dados *online* e melhorar o algoritmo de mineração de dados usando dados históricos de sensores para garantia do desempenho do processamento.
Desenvolvimento de modelos de medição	[27]	Desenvolver pesquisas em computação em nuvem e pesquisa sobre a inteligência computacional, incluindo aprendizado profundo.
	[28]	Desenvolver tecnologias para coletar, armazenar e processar dados, bem como aplicar a *big data* na transformação digital associada de inovação e novos modelos de negócios.
	[8]	Desenvolvimento de modelos teóricos de pesquisa em estudos exploratórios futuros e amplos usando análise estatística para a modelagem de equações estruturais; Aplicação de outras técnicas de *decision making*, como preferência por similaridade com a solução ideal e *Analytic Network Process,* combinados com técnicas sofisticadas de computação para produzir resultados mais interessantes; Realizar a comparação entre as perspectivas de diferentes de clientes, funcionários e fornecedores; e Mensusrar o impacto da adoção de *big data* investigando desempenho financeiro e não financeiro das empresas de manufatura.
Implementação e aperfeiçoamento	[4]	Avançar em um ambiente de *cyber-physical* production systems CPPS de forma *online,* onde o controle em tempo real será mais desafiador.
	[29]	Empregar a computação quântica para fins de aprendizado de máquina e poder ajudar a destronar “lei de Moor”, fornecendo mais espaço de processamento por unidade de tempo.
	[30]	Aperfeiçoar a exploração dos dados com a utilização do *Big Data Analytics* (BDA) para contribuir com a melhoria das operações e destacar seu desempenho.

Tabela 2. Continuação: Relação das oportunidades identificada no Portfólio Bibliográfico

Aspectos de Avaliação	Autores	Pesquisas Futuras
Medição dos dados	[9]	A realização da medição de desempenho para *smart manufacturing systems* (SMS).
	[5]	Estimular a abordagem sobre o desenvolvimento de novas Tecnologias *internet of manufacturing things* (IoMT) e metodologias analíticas para melhorar serviços de manufatura e otimizar os sistemas de manufatura.
Replicação	[31]	Replicar as descobertas sobre papel das tecnologias digitais para o serviço na transformação de empresas industriais.
Avaliação do sucesso	[26]	Desenvolver pesquisa utilizando uma rede bayesiana para expressar as dependências causais entre os constructos usando probabilidades condicionais, considerando o tipo de *tecnologia para a indústria 4.0* como o variável moderada para estudar o efeito da pratica *lean manufacturing* na *sustentabilidade organisational performance*; Desenvolvimento de um sistema de apoio à decisão que possa ser usado para prever a *sustentabilidade organisational performance para* completar os estudos longitudinais e entender, como implantação das tecnologias da indústria 4.0 influenciam nas conclusões do presente estudo no futuro.

4.4 Modelo para medição do desempenho de equipamento

De acordo com as oportunidades identificadas no Portfólio Bibliográfico, relatado pela Tabela 2 construída com base nas sugestões de pesquisas futuras inspiradas pelos autores [3, 4, 5, 6, 7, 8, 9, 26, 27, 28, 29, 30, 31] apresenta-se uma proposta de um modelo para medição de desempenho baseada em dados para máquinas**,** ilustradas pela (Fig.6), contemplando a integração deste modelo por três camadas, sendo elas:

***Manufatura* (*Entradas*)**: Este módulo acomoda diferentes tipos de atividades e consiste na entrada de informações e recursos para a produção da manufatura e a coleta de dados aplicada por meio do monitoramento *online*, onde: **A máquina**: informações da capacidade produtiva e parâmetros de produção, tais como: tipo de produtos, produção/hora entre outros; **Processo:** Determinar o processo de acordo com o tipo de produto. Por exemplo: produto 1- linha a, b, c; Produto 2 – linha b, c, d; **Informação:** Toda a informação do processo será enviada para ser processada; **Pessoas:** o recurso mais importante da operação será responsável por lançar dados no sistema e interpretar os dados monitorados para serem analisados e decisões serem tomadas;

Análise de dados* (*Transformação de Processos*)**: Este módulo consiste em duas funções: ***Armazenamento: utilizado para o armazenamento dos dados coletados e

Processamento de dados: dados coletados serão processados para gerar informações relevantes do processo;

Medição do desempenho (Saídas): O módulo permite a gestão visual das informações dos dados coletados e processados de forma *online* para auxiliar as tomadas de decisões para o gerenciamento da produção. Os dados podem ser apresentados por indicadores chaves do desempenho, no qual possibilita não só a gestão da produção, como também a operação da produção, a enxergar de forma clara, o desempenho monitorado do equipamento.

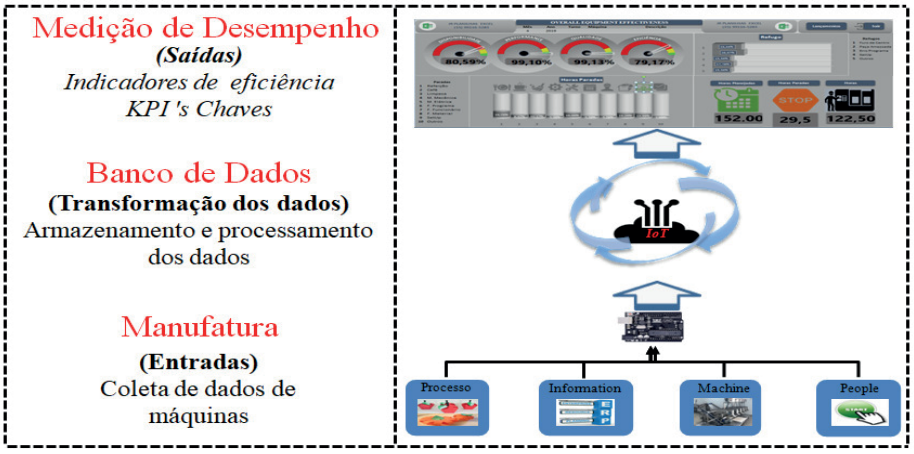

Fig.6. Manufatura Conectada

4. Conclusão

A **Análise Bibliométrica** composto por 13 artigos selecionados apresentou como resultado os seguintes dados: Os artigos foram selecionados em 12 periódicos indexados no JCR, sendo que a melhor classificação obtida foi pelo Periódico, "Technological Forecasting and Social Change" com posição no ranking de n° 1.784. O periódico com o maior grau de relevância foi o "*International Journal of Production Research*", o qual apresentou dentre os demais, duas publicações selecionada para o Portifólio Bibliográfico. No que tange o reconhecimento científico dos artigos do Portfólio Bibliográfico publicados entre o anos de (2013 e 2019), todos obtiveram índice de citação no Google Scholar, sendo o artigo com o maior número de citação (127) está intitulado como "*Deep learning for smart manufacturing: Methods and applications* publicado em (2018)".

Para o grau de reconhecimento dos 50 autores identificados no Portfólio Bibliográfico considerou-se o fator de impacto cientifico dos artigos publicados em nas bases medidas pelo (JCR) e as citações dos autores em outras publicações medidas por meio da plataforma Google Scholar, neste quesito, 15 autores não foram localizados na

plataforma, os demais apresentaram reconhecimento científico relevante. Quanto às análises dos termos de buscas foram identificados 62 termos, destes 55% também compõe os termos de buscas que foram utilizadas nos eixos da pesquisa e estão classificados entre os 10 primeiros mais citados nos artigos do Portfólio Bibliográfico.

A revisão sistemática possibilitou buscar na literatura, alguns dos principais artigos reconhecidos cientificamente, para tomar conhecimento sobre quais temas estão sendo tratados pelos pesquisadores na atualidade, sobre a medição de desempenho. Desta forma, possibilitou conhecer, quais periódicos são os mais relevantes sobre o tema de pesquisa, quais termos de buscas está sendo utilizados nas publicações e identificar neste portifólio, quais contribuições podem ser relevantes para serem aplicadas em pesquisas futuras. Neste contexto, o objetivo da pesquisa sobre a avaliação de como esta sendo tratada, a medição de desempenho baseada em dados para máquinas, no contexto da indústria 4.0 foi alcançado, pois com base nas propostas de contribuições inspiradas em pesquisas futuras para avanço da área, foi proposto um modelo medição do desempenho com base em dados de máquinas, compondo-se de três módulos (*manufatura, banco de dados e medição do desempenho*) para coletar, armazenar e transformar os dados em informações a ser gerenciadas por meio de indicadores. Com este resultado da-se por concluída a pesquisa, tendo como o objetivo proposto sendo alcançado e os resultados como satisfatórios.

Para futuras pesquisas, mesmo considerando que já existe algo pronto como (ferramentas/algoritmos e outras tecnologias de dados maduras) cabem a implementação e a avaliação dos resultados desta proposta.

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Estimación del nivel de servicio en un laboratorio de análisis materiales

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Resumen.
Un laboratorio de análisis de materiales para obras de ingeniería civil proporciona servicios a la población, sin embargo, actualmente el tiempo requerido para realizar cada prueba no está documentado, simplemente se deja al conocimiento del personal técnico; es decir, cuando llega un cliente y solicita algún servicio, la persona que los atiende, de acuerdo con su experiencia, le proporciona el tiempo aproximado de entrega. El proceso inicia llenando una solicitud y finaliza entregando el informe de resultados, previo al llenado de una encuesta de calidad. El objetivo de este artículo se enfoca en dos aspectos relevantes para la evaluación y análisis de un servicio, primero, se definen indicadores de desempeño y después se modela e implementa el modelo de simulación para estimar valores resultantes para el proceso en estudio, con base en ambos, será posible evaluar y analizar el sistema a desarrollar para seleccionar las propuestas de mejora. El trabajo sigue una metodología de 5 pasos, siendo: (1) análisis de datos, (2) descripción de elementos de soporte, (3) establecimiento de KPIs, (4) definición de procesos operativos del laboratorio y (5) implementación de un modelo de simulación. Con la ejecución de esta metodología fue posible estimar el nivel de servicio del proceso, y es posible simular los valores esperados para futuras operaciones del laboratorio con la finalidad de evaluar los KPIs y a partir de estos mejorar el nivel de servicio de los clientes.

Palabras clave: Laboratorio de materiales, órdenes de trabajo, desempeño, KPI's, simulación

1. Introducción

La medición del desempeño en los procesos u operaciones que realiza una empresa, permiten conocer si están siendo realizados conforme al nivel esperado, los indicadores claves de desempeño (KPIs) son métricas muy utilizadas para determinar el cumplimiento de las actividades en una empresa Toor & Ogunlana (2009) consideran que los KPIs son útiles, ya que permiten comparar el desempeño actual contra el esperado en términos de efectividad, eficiencia y calidad; así mismo los KPIs permiten evaluar el desempeño de todas las partes involucradas en la cadena Sellitto et al. (2015) a través de los Operadores de Referencia de la Cadena de Suministro (SCOR) que consisten en procesos estandarizados de la cadena de abastecimiento, métricas y atributos de desempeño normalizados, prácticas y habilidades laborales tipificadas; consideran que el SCOR permite evaluar la confiabilidad, la capacidad de respuesta, la agilidad, y los costos.

Los KPIs deben representar las necesidades y objetivos de la empresa, y al mismo tiempo deben estar orientados a la misión y visión, tal como Shahin y Mahbod (2006) indican que los KPIs reflejan y se derivan a partir de los objetivos de la organización, así mismo, cada indicador debe estar basado en criterios que permitan su posterior análisis, Palma (2014) considera que las métricas utilizadas en el nivel uno de los modelos SCOR son KPIs y la función de estos es medir y expresar el rendimiento general de una característica en específico, Gunasekaran et al. (2004) consideran que la medición del desempeño de las cadenas de suministro se puede realizar en tres niveles: estratégico, operacional y táctico, así mismo, las métricas utilizadas para medir el desempeño y el mejoramiento en cada nivel deben capturar verdaderamente la esencia del desempeño organizacional.

Al momento de realizar algún proyecto es de gran importancia evaluar el desempeño logrado durante el avance del mismo, por lo que es necesario establecer indicadores que determinen si el desempeño se encuentra en el nivel deseado, Ogunsanmi (2013) menciona que los KPIs pueden ser utilizados para identificar las fortalezas y debilidades en proyectos compartidos entre el sector público y privado, además de ser herramientas útiles para la gestión del desempeño de los proyectos, Ugwu y Haupt (2005) hacen referencia que al momento de desarrollar estrategias efectivas para entornos sustentables en la construcción, es necesario considerar 3 elementos claves: 1) una formulación clara y establecimientos de objetivos, 2) identificar y evaluar alternativas en términos cuantitativos y/o cualitativos y 3) una implementación efectiva de la alternativa seleccionada; por lo que, para desarrollar el segundo punto es necesario establecer KPIs que permitan evaluar aquellas alternativas que sean establecidas en ambos términos.

Cuando es requerido establecer KPIs se debe considerar que no todos los indicadores son aplicables a los mismos proyectos o empresas, estos no deben ser vistos de manera general, dependiendo de las necesidades del proyecto o de la industria, y en conjunto con la misión, visión y objetivos establecidos, los KPIs determinan diferentes aspectos. Kang et al. (2016) realizan una descripción detallada de los KPIs utilizados en su investigación, consideran elementos de soporte como tiempo, cantidad y mantenimiento, luego se establecen las relaciones entre cada elemento que servirán para medir aspectos específicos dentro del sistema.

Al tratar de replicar o imitar el comportamiento de algún sistema o las operaciones que realiza una empresa, es necesario apoyarse en técnicas de simulación de procesos. Gómez et al. (2015) hacen referencia que la simulación puede ser utilizada con la finalidad de dar solución a problemas reales, mediante el análisis y descripción del comportamiento del sistema, así mismo Rouzafzoon (2016) recreó los servicios ofrecidos en un hospital, considerando que para medir el desempeño de los resultados en el modelo de simulación es necesario establecer KPIs, el autor considera el nivel de servicio como un aspecto crítico en la administración de los hospitales.

Para reproducir la forma en que una empresa está operando, es necesario describir todos los procedimientos que son realizados, desde la solicitud de algún servicio o bien la contratación para elaborar algún producto, Sánchez et al. (2015) consideran que para desarrollar el proceso de simulación se debe tomar en cuenta como insumo la estructura real del proceso productivo, de esta manera, se deben detallar todos aquellos procedimientos involucrados para cumplir los requerimientos de los clientes.

Por lo anterior mencionado, y en referencia a lo que se hizo, se tienen que considerar todas las entradas al sistema como la cantidad de presupuestos a elaborar, la cantidad de órdenes de trabajo (OT) a cumplir, así mismo, todos aquellos insumos que son necesarios para atender los requerimientos de la demanda de los seis tipos de servicios.

Para todo esto se requiere poseer un amplio conocimiento de los procesos de transformación, por ejemplo, qué proceso es necesario realizar para transformar un presupuesto en el resultado de una prueba solicitada, así como los tiempos que tarda la elaboración de la prueba, y finalmente conocer las salidas del sistema real (porcentaje de OT, el ingreso neto obtenido, entre otras). Así mismo, es importante caracterizar correctamente todas estas variables, ya que permitirán establecer las bases para desarrollar el modelo de simulación con el uso de algún software y establecer escenarios, para identificar la manera más eficiente de gestionar los recursos del laboratorio frente a diferentes condiciones de demanda, decisiones que se tomarían a partir de la generación de los KPIs en cada escenario evaluado.

El artículo está estructurado de la siguiente manera: en la sección 2, se describe la metodología aplicada para atender el caso de estudio; en la Sección 3 se explica el caso de estudio, así como los elementos necesarios para establecer los KPIs y el modelo de simulación; en la Sección 4 se muestran los resultados obtenidos, y en la última sección se discuten los principales hallazgos y las conclusiones del presente trabajo.

2. Descripción del Método

Las herramientas de simulación permiten recrear el comportamiento de las actividades que realiza una empresa. Gómez et al. (2015) consideran que mediante la simulación se pueden desarrollar escenarios de sistemas complejos con el objetivo de comprender su comportamiento. Los modelos de simulación de acuerdo con Morales et al. (2013) están compuestos por un conjunto de representaciones, expresadas como relaciones matemáticas, lógicas o simbólicas, entre las entidades que interactúan en el sistema, pues a través de la simulación es posible conocer aspectos fundamentales en la opera-

ción de las empresas. Sánchez et al. (2015) consideran que la aplicación de esta herramienta ofrece una alternativa para conocer de forma correcta los puntos críticos que pueden tener los procesos de producción y plantear soluciones que aumenten la eficiencia y disminuyan el tiempo de ejecución de diferentes actividades.

Para establecer las bases necesarias para el desarrollo de un modelo de simulación Andrés et al. (2016) consideran necesario diferenciar 3 tipos de variables dentro del sistema. En la tabla 1 se muestran los tipos de variables:

Tabla 1. Clasificación de Variables

Tipo de variable	Descripción
De Nivel	Representan acumulaciones del sistema, normalmente son las variables más importantes y muestran cada instante la situación del modelo, cada variable de nivel está asociada a una o varias variables de flujo.
De Flujo	Determinan la variación de los niveles, recogen las acciones resultantes de las decisiones tomadas en el sistema, determinando las variaciones de los niveles.
Auxiliares	Son parámetros que permiten una mejor visualización de los aspectos que condicionan el comportamiento de los flujos.

Fuente: Modificada a partir de Campuzano et al. (2010), Andrés et al. (2016)

La metodología que se propone se presenta en la figura 1:



Figura 1. Diagrama de la metodología para abordar el caso de estudio
Fuente: Elaboración propia

En el primer paso se realiza la recolección de todos los datos iniciales relacionados a la atención de órdenes de trabajo del laboratorio del caso de estudio, posteriormente en la descripción de los elementos de soporte se detallan los elementos que son susceptibles a contabilizar como el número de presupuestos, los presupuestos confirmados (OT), tiempo de confirmación, etc. Para el establecimiento de KPIs, es necesario describir la relación que guardan los elementos de soporte y con base en ello, establecer los indicadores que permiten conocer la situación actual del laboratorio del caso de estudio.

Luego, para el desarrollo de los procesos operativos se menciona de manera general los procesos que son realizados, así como el tiempo que tardan en completar las órdenes de trabajo. Finalmente, para el desarrollo del modelo de simulación es necesario contar con las bases anteriormente mencionadas, para así establecer los parámetros que permitan estimar el nivel requerido de los KPIs. Cabe mencionar que la administración de laboratorio del caso de estudio, no está a cargo de los autores.

3. Aplicación de la metodología al caso de estudio

Este laboratorio se encarga de realizar análisis de materiales para la construcción, las pruebas están orientadas a acero, concreto hidráulico, concreto asfaltico, elementos prefabricados, geotecnia y topografía, que mediante el análisis de estas pruebas es posible conocer las propiedades físicas de los materiales en cuestión, la forma en que se atiende una OT se muestra en la figura 2

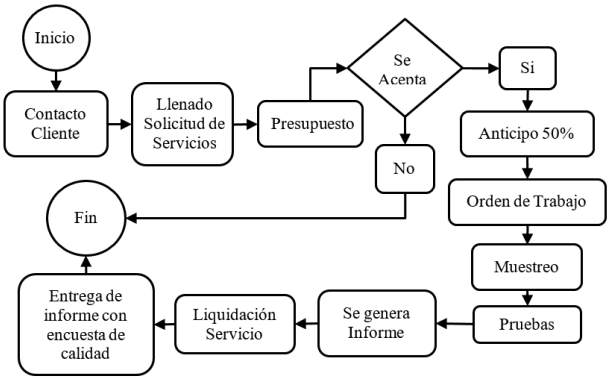

Figura 2. Procesamiento de órdenes de trabajo
Fuente: Elaboración propia

Según la figura 2, se inicia con el llenado de solicitud de un servicio para realizar un presupuesto de alguna de las pruebas ya mencionadas, cuando los clientes aceptan el presupuesto, se considera confirmado y se convierte en una OT, por lo tanto, a partir de este momento el tiempo de servicio inicia y una vez que la última prueba ha sido realizada se detiene el tiempo que tarda una OT en ser completada. Debido a la naturaleza del laboratorio, no se considera el tiempo en que se genera el informe, ya que este es elaborado una vez que las pruebas son terminadas y se entrega al momento de la liquidación de los servicios.

En la figura 3 se observa de manera general la operación del laboratorio.

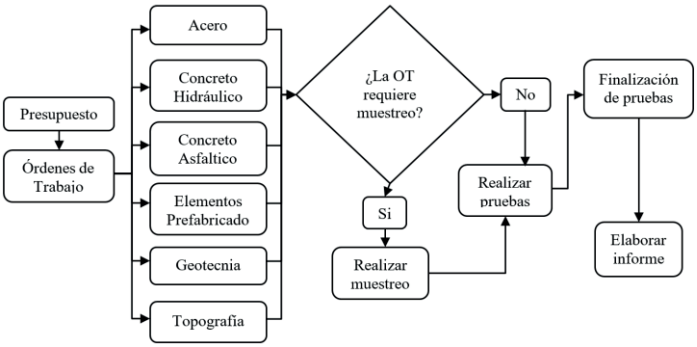

Figura 3. Operación general del laboratorio
Fuente: Elaboración propia

La figura 3 indica que los presupuestos que son recibidos, sin embargo, solo un porcentaje de los presupuestos solicitados se convierten en una OT, dependiendo de la preferencia de los clientes puede ser cualquiera de los 6 servicios previamente mencionados, así mismo, conforme al tipo de servicio de la OT ésta requerirá un muestreo y diferentes pruebas serán realizadas.

Las cifras reales obtenidas a cerca de los prepuestos y órdenes de trabajo que solicitaron los clientes de manera mensual durante el año 2019, se presentan en la tabla 2 y en la tabla 3, en la cual las abreviaturas corresponden de la siguiente manera:

- PRE = Presupuesto
- AC = Acero
- CAS = Concretos Asfalticos
- CHA = Concretos Hidráulicos
- EP = Elementos Prefabricados
- GA = Geotecnia
- MULTI = Múltiple
- CONF = Confirmación

Tabla 2. Porcentajes de confirmación de OT del año 2019

Mes	PRE AC	OT AC	PRE CAS	OT CAS	PRE CHA	OT CHA	PRE EP	OT EP	PRE GA	OT GA	PRE MULTI	Total PRE	Total OT	% CONF
1	2	2	0	0	3	3	0	0	11	2	0	16	7	43.75
2	**3**	**3**	**0**	**0**	**6**	**3**	**0**	**0**	**8**	**3**	**1**	**18**	**10**	**50.00**
3	0	0	0	0	4	2	1	1	12	3	2	19	6	31.58
4	**8**	**8**	**0**	**0**	**5**	**5**	**1**	**0**	**12**	**3**	**0**	**26**	**16**	**61.54**
5	1	0	0	0	2	2	0	0	8	2	2	13	4	30.77
6	1	1	2	2	1	1	0	0	11	2	2	17	6	35.29
7	0	0	1	0	4	2	0	0	6	1	0	11	3	27.27
8	**2**	**1**	**2**	**0**	**7**	**5**	**0**	**0**	**8**	**4**	**0**	**19**	**10**	**52.63**
9	**0**	**0**	**1**	**0**	**8**	**7**	**0**	**0**	**11**	**3**	**0**	**20**	**10**	**50.00**
10	2	0	0	0	4	3	0	0	9	4	0	15	7	46.67
11	3	2	1	0	6	5	0	0	5	1	1	16	8	50.00
12	0	0	0	0	1	1	0	0	5	2	1	7	3	42.86
Total	22	17	7	2	51	39	2	1	106	30	9	197	90	45.66

Tabla 3. Porcentajes de confirmación y preferencia de servicio del año 2019

Porcentajes	AC	CAS	CHA	EP	GEO	MULTI	Confirmación General
% Confirmación por servicio	77.27	28.57	76.47	50.00	28.30	0.0	45.69
% Preferencia por servicio	11.17	3.55	25.89	1.02	53.81	4.57	100%

La figura 4 muestra la preferencia de los clientes para el año 2019.

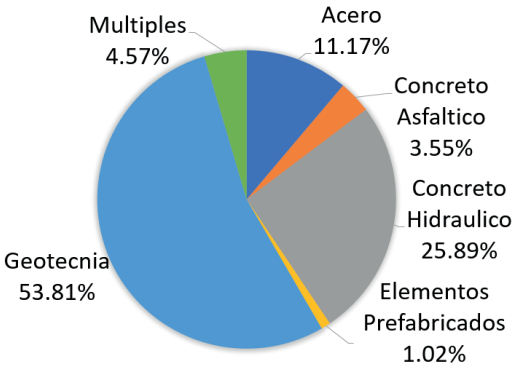

Figura 4. Preferencia de los servicios del año 2019 para los 6 tipos de servicios
Fuente: Elaboración propia

Existe una preferencia muy marcada para los servicios de geotecnia y concreto, así mismo, estos porcentajes servirán como base para establecer la distribución del tipo de servicio solicitado en los presupuestos.

En la tabla 2 se puede observar que existe una mayor carga de trabajo en los meses de febrero, abril, agosto, septiembre y noviembre, debido a que más del 50% de los presupuestos fueron confirmados, así mismo casi todos estos meses se confirmaron más de 10 órdenes de trabajo, estos datos serán utilizados para realizar la simulación, por ejemplo, para el mes de abril de un total de 26 presupuestos recibidos solamente se confirmaron aproximadamente el 61.54%, por lo que, 16 órdenes de trabajo deberán ser atendidas.

La categorización de los datos se realizó de la siguiente manera:

1) Fecha de solicitud de presupuesto
2) Tipo de servicio
3) Fecha de orden de trabajo
4) Descripción del servicio solicitado
5) Fecha de entrega de la orden de trabajo

De esta manera es posible conocer la fecha en que un presupuesto fue solicitado y el tiempo que tarda en confirmar el cliente (fecha de OT), los tipos de órdenes y la descripción de los servicios que solicitan los clientes permiten tener una estimación del tiempo necesario para atender la OT; en resumen, se pueden conocer todas las entradas del sistema.

3.1 Establecimiento de los KPIs

Para determinar si el nivel de servicio está siendo alcanzado a la meta fijada, en la tabla 4 se puede observar los KPIs establecidos:

Tabla 4. Indicadores claves de desempeño a considerar de forma general.

KPI	Cálculo
% de confirmación por servicio (1)	%CS = PRE Confirmados / PRE Recibidos
% de confirmación Total (2)	%CT = PRE Totales Confirmados / PRE Totales Recibidos
Órdenes atendidas (3)	OA = Total de órdenes atendidas
Órdenes en atención (4)	OEA = Total de órdenes en proceso
% de atención de órdenes (5)	%AO = Órdenes atendidas / Órdenes en el sistema

3.2 Desarrollo de los procesos operativos

Para desarrollar el modelo de simulación primeramente es necesario describir el proceso real que sigue el laboratorio, en la figura 5 y 6 se muestra el proceso:

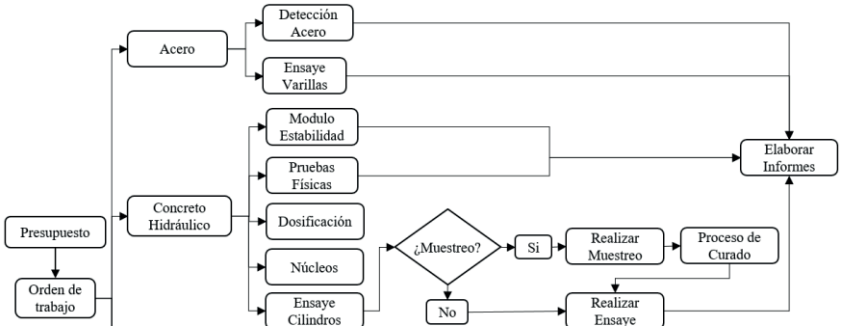

Figura 5. Procedimientos para los servicios de AC y CHA
Fuente: Elaboración propia

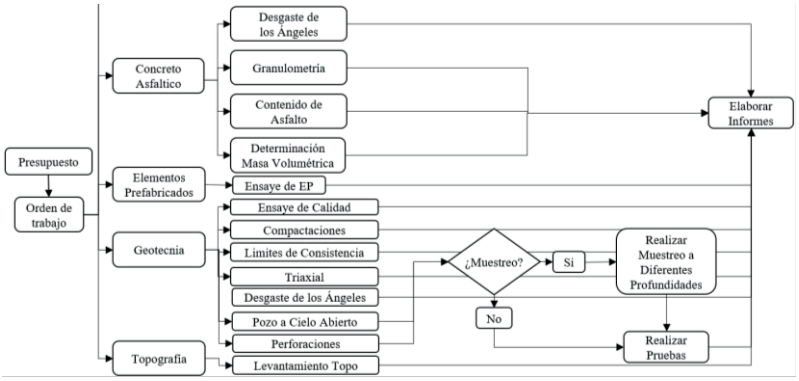

Figura 6. Procedimientos para los servicios de CAS, EP, GEO y Topografía
Fuente: Elaboración propia

De la figura 5, se inicia el proceso recibiendo la solicitud de presupuestos, la cual no necesariamente es la misma de manera diaria, así mismo, se asigna un número de presupuesto que permite realizar procesos de trazabilidad; un porcentaje de estos presupuestos es confirmado lo cual procede a convertirse en una OT, por ejemplo, en la tabla

2 para el mes de abril existe una probabilidad de casi el 62% de que un presupuesto se confirme (OT) y de nuevo se establece un número de OT dependiendo del tipo de servicio contratado, el número de OT está ligado con el número de presupuesto.

La forma en que se procede a atender las OT es considerando la disciplina de líneas de espera FIFO; es decir, las primeras OT que ingresan al laboratorio deben ser las primeras en salir, sin embargo, el tiempo de ejecución de las pruebas es variable y esto provoca que, para las salidas (entrega del informe) no se observe ese comportamiento.

De los seis tipos de servicio, en cuatro de ellos, se requiere el traslado del personal al sitio donde se realiza la obra de construcción para extraer muestras de material; en otros casos, los clientes llevan sus muestras, por lo que este tiempo es considerado en la duración de ejecución de las pruebas.

Una vez que todas las pruebas han sido ejecutadas los resultados son reportados en los libros correspondientes, estos sirven como base para elaborar los informes de los clientes, por último, se le solicita al cliente la liquidación de los servicios, que al término de esta se le entrega el informe y se finaliza el proceso con aplicación de la encuesta de calidad de servicio.

3.3 Desarrollo del modelo de simulación

Para replicar el comportamiento del laboratorio a través de un modelo de simulación, fue necesario determinar las propiedades del sistema real, las cuales son establecidas de me manera previa, y que a su vez debe permitir que varíen durante el proceso de la simulación (Chase, & Aquilano, N. J., 2009).

Para el desarrollo del modelo de simulación fue necesario el uso de herramientas computacionales que permitieron recrear la manera en la cual el laboratorio procesa las OT, eligiéndose el software Arena® ya que en su versión estudiantil ofrece los recursos necesarios para la implementación del modelo y para realizar la simulación se utilizó una computadora personal con un procesador Intel Core i3, con una memoria RAM 4.0 GB y con un sistema operativo de 64 bits.

3.3.1 Definición de parámetros

Para la ejecución del proceso de simulación serán considerados los meses en los cuales hubo 10 o más OT confirmadas (febrero, abril, agosto y septiembre), los parámetros bajo los cuales el modelo de simulación se regirá se muestran en las tablas 5 y 6 en las cuales PRO = Probabilidad

Tabla 5. Parámetro de probabilidad de pruebas y confirmación por mes

Tipo de Servicio	% PRO PRE Mes 2	% PRO CONF Mes 2	% PRO PRE Mes 4	% PRO CONF Mes 4	% PRO PRE Mes 8	% PRO CONF Mes 8	% PRO PRE Mes 9	% PRO CONF Mes 9
AC	17	100	31	100	11	50	0	0
CAS	0	0	0	0	11	0	5	0

CHA	33	50	19	100	36	71	40	88
EP	0	0	4	0	0	0	0	0
GA	44	38	46	25	42	50	55	28
MULTI	6	-	0	-	0	-	0	-

En la tabla 5 no se consideran los presupuestos múltiples, debido a que este en tipo de solicitudes, los clientes sólo preguntan para conocer el costo de los servicios.

Tabla 6. Parámetro de probabilidad de pruebas por tipo de servicio por cada mes

Tipo de prueba	% PRO prueba Mes 2	% PRO prueba Mes 4	% PRO prueba Mes 8	% PRO prueba Mes 9
Acero				
Detección de Acero	25	0	0	0
Ensaye de Varillas	75	100	100	0
Cantidad de muestras de varillas de acero				
1 Muestra de varillas	67	0	0	0
2 Muestras de varillas	0	100	0	0
3 Muestras de varillas	33	0	100	0
4 Muestras de varillas	0	0	0	0
Concretos Asfalticos				
Desgaste de los ángeles en materiales pétreos	25	25	25	25
Granulometría	25	25	25	25
Contenido de asfalto y granulometría	25	25	25	25
Determinación de masa volumétrica	25	25	25	25
Concretos Hidráulicos				
Módulo de elasticidad	0	0	20	0
Pruebas físicas	0	20	0	14
Dosificación	0	0	0	0
Extracción y ensaye de núcleos	67	20	0	0
Muestreo y ensaye de cilindros de concretos	33	20	0	14
Ensaye de cilindros	0	40	80	72
Elementos Prefabricados				
Ensaye de elementos prefabricados	0	0	0	0
Geotecnia				
Muestreo Pozo a Cielo Abierto y ensayes (PCA)	33	0	25	67
Prueba de perforación estándar y ensayes (SPT)	67	67	0	0
Ensaye de calidad	0	33	0	33
Compactaciones	0	0	0	0

Límites de consistencia	0	0	75	0
Triaxial	0	0	0	0
Desgaste de los ángeles	0	0	0	0
Ensaye de rocas	0	0	0	0
Tipo de prueba PCA				
1 PCA a 3 metros	20	20	20	20
2 PCA a 3 metros	20	20	20	20
3 PCA a 3 metros	20	20	20	20
7 PCA a 3 metros	20	20	20	20
1 PCA a 4.5 metros	20	20	20	20
Tipo de prueba SPT				
1 SPT a 5 metros	20	20	20	20
1 SPT a 10 metros	20	20	20	20
1 SPT a 15 metros	20	20	20	20
2 SPT a 5 metros	20	20	20	20
3 SPT a 30 metros	20	20	20	20

3.3.2 Definición de variables

Variables de nivel
Estas variables permiten acumular las OT y solo varían de acuerdo al comportamiento de las variables de flujo, dentro del modelo se consideran las siguientes:

Llegadas de presupuestos: representa la cantidad de presupuestos que llegan de manera diaria

OT sin confirmar: indican la cantidad de presupuestos que no fueron confirmados

OT atendidas: son todas las OT que fueron completadas

Variables de flujo
Este tipo de variables determinan la variación de los niveles, así mismo recolectan la información que resulta a partir de las acciones tomadas dentro del sistema, para el desarrollo del modelo se considera el tiempo necesario para realizar las pruebas de los servicios correspondientes, el tiempo de ejecución está considerado en días, en la tabla 7 se muestra las distribuciones que fueron establecidas para la ejecución del modelo de simulación.

Variables auxiliares
Para el caso de estudio, no fue necesario recurrir a este tipo de variables.

Tabla 7. Distribuciones para las variables de flujo

Proceso	Distribución
Llega presupuestos febrero	Triangular (1,1,4)
Llega presupuestos abril	Triangular (1,2,10)
Llega presupuestos agosto	Triangular (1,1,6)
Llega presupuestos septiembre	Triangular (1,1,5)
Prueba_Deteccion_Acero	Uniforme (1,2)
Ensaye 1M de varillas	Uniforme (1,2)
Ensaye 2M de varillas	Triangular (1,2,3)
Ensaye 3M de varillas	Triangular (2,2,4)
Ensaye 4M de varillas	Triangular (2,3,5)
Desgaste_Ang_MP	Uniforme (1,2)
Granulometría	Triangular (1,2,4)
Con_Asfalto_Granu	Triangular (2,3,4)
Deter_Masa_Vol	Triangular (1,1,3)
Modulo_Elasticidad	Constante (1)
Pruebas_Fisicas	Triangular (2,3,5)
Dosificación	Triangular (3,5,8)
Núcleo	Triangular (4,7,10)
Muestreo_Prueba_Cilindros	Constante (28)
Ensaye_Cilindros	Constante (1)
Ensaye EP	Triangular (1,2,4)
1_PCA_3m	Triangular (3,4,7)
2_PCA_3m	Triangular (3,4,7)
3_PCA_3m	Triangular (3,5,8)
7_PCA_3m	Triangular (5,8,10)
1_PCA_4_5m	Triangular (3,4,7)
1_SPT_5m	Triangular (3,5,7)
1_SPT_10m	Triangular (5,7,12)
1_SPT_15m	Triangular (7,10,14)
2_SPT_5m	Triangular (3,5,7)
3_SPT_30m	Triangular (21,25,30)
Ensaye_Calidad	Triangular (5,7,9)
Comp	Triangular (3,5,7)
Limites_Cons	Triangular (1,2,4)
Triaxial	Triangular (1,3,4)
Desg_Angeles	Triangular (1,2,4)
Ensaye Rocas	Uniforme (2,4)

4. Resultados

La ejecución del modelo de simulación se realizó considerando los meses que contaron con 10 o más OT confirmadas, las cuales representan también un mayor nivel de confirmación (50% o más), la duración de la simulación fue 30 días. En la tabla 8 se muestran los resultados, en la tabla 9 se observan los KPIs resultantes del proceso de simulación y en la tabla 10 se muestran los KPIs obtenidos a partir de los datos del año 2019

Tabla 8. Resultados del modelo se simulación

OT	Mes 2	Mes 4	Mes 8	Mes 9
Presupuestos recibidos	18	8	12	13
OT confirmadas	4	5	3	6
OT rechazadas	14	3	11	7
OT atendidas	3	5	3	6
OT en proceso	1	0	0	0

Tabla 9. KPIs obtenidos, según el modelo de simulación

KPI	Mes 2						Mes 4					Mes 8					Mes 9				
	AC	CAS	CHA	EP	GA	MUTI	AC	CAS	CHA	EP	GA	AC	CAS	CHA	EP	GA	AC	CAS	CHA	EP	GA
PRE	1	0	4	0	11	2	0	0	3	0	5	0	4	4	0	4	0	0	3	0	10
OT	1	0	3	0	0	0	0	0	3	0	2	0	0	3	0	0	0	0	3	0	3
%CS	100	0	75	0	0	0	0	0	100	0	40	0	0	75	0	0	0	0	100	0	30
%CT				22.22						62.50					25.00					46.15	
OA	1	0	2	0	0	0	0	0	3	0	2	0	0	3	0	0	0	0	3	0	3
OEA	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
%AO				66.67						100.00					100.00					100.00	

Tabla 10. KPIs obtenidos de acuerdo a los datos del año 2019

KPI	Mes 2						Mes 4					Mes 8					Mes 9				
	AC	CAS	CHA	EP	GA	MUTI	AC	CAS	CHA	EP	GA	AC	CAS	CHA	EP	GA	AC	CAS	CHA	EP	GA
PRE	3	0	6	0	8	1	8	0	5	1	12	2	2	7	0	8	0	1	8	0	11
OT	3	0	2	0	3	0	8	0	5	0	3	1	0	5	0	4	0	0	7	0	3
%CS	100	0	33.33	0	37.5	0	100	0	100	0	25	50	0	71.42	0	50	0	0	87.5	0	27.27
%CT				44.44						61.53					52.63					50	
OA	3	0	2	0	3	0	8	0	4	0	2	1	0	5	0	4	0	0	7	0	3
OEA	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0
%AO				100						87.5					100					100	

Para el mes 2, logró una atención en las OT del 66.67%; es decir, una de las tres órdenes se quedó en proceso, esto se debe a que una de las OT fue de CHA y fue de la prueba de muestreo y ensaye de cilindros, la cual tiene una durabilidad de 28 días, conforme a la norma NMX-C-159-ONNCCE-16, considera que para pruebas de concreto hidráulico, es necesario 28 de curado para su análisis de resistencia a la compresión. En el mes 4, se tuvo una orden de atención del 100%; es decir, se atendieron las cinco órdenes que llegaron, lo cual demuestra que atendiendo esa cantidad de OT es posible cumplir los requerimientos de los clientes, del mismo modo para el mes 8 y 9, se obtuvo el 100% de atención de las órdenes que ingresaron, siendo estas 3 y 6 respectivamente.

5. Conclusiones

A través del establecimiento de los parámetros para los 4 meses con mayor cantidad de OT confirmadas, es posible conocer el comportamiento del laboratorio. Así mismo, considerando este nivel de trabajo, el laboratorio es capaz de atender la demanda de los meses restantes, tomando en cuenta los parámetros establecidos. En la tabla 9 se puede observar que la preferencia sobre los servicios de GA y CHA siguen manteniéndose comparado con la tabla 3, sin embargo, los porcentajes de confirmación por cada mes fueron menores.

Mediante la aplicación de herramientas de simulación, fue posible determinar si el laboratorio está atendiendo las OT con el nivel de atención esperado, como se puede observar en la tabla 9 el laboratorio puede atender correctamente las OT que ingresan a él, para los 4 meses establecidos.

Comparando las tablas 9 y 10 es posible observar que el indicador %AO tiene un rendimiento similar considerando la propuesta del modelo de simulación, sin embargo, esto se debe a que la mayoría de las pruebas entrantes tienen un corto tiempo de duración, así mismo, se debe considerar que aquellas órdenes que llegan a final de mes no podrán ser completadas durante el mismo mes, lo que a primera vista podría ser indicativo de un bajo rendimiento, en cambio, una forma de considerar el nivel de atención sería contemplarla para el mismo mes, de esta forma no afectaría los meses consecuentes.

A partir de los resultados obtenidos, se puede concluir que actualmente el laboratorio se encuentra operando con un nivel de servicio cercano al 100%, mediante el establecimiento de los KPIs fue posible determinar el nivel de servicio que el laboratorio está ofreciendo hacia los clientes, de la misma forma, con las métricas establecidas se puede detectar alguna alteración en la atención de las OT para cada tipo de servicio, o bien, reforzar los procedimientos para seguir garantizando el nivel de servicio esperado por los clientes.

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Despacho óptimo de buses eléctricos bajo incertidumbre en los tiempos de viaje

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Resumen. Actualmente, Santiago de Chile es la segunda ciudad del mundo con más buses eléctricos y uno de los problemas importantes que debe abordar el sistema de transporte público es el despacho óptimo de estos, teniendo en cuenta una programación de salidas dada y tiempos de viajes que son considerados estocásticos. En este trabajo se contempla planificar los despachos de dos almacenes de buses en un día completo de operación, dividido en ciertas franjas horarias, en las cuales se tiene determinados comportamientos de los tiempos de viaje y disponibilidad de buses. Se formula un modelo de optimización estocástica con recurso de múltiples etapas y se resuelve una instancia en particular para así determinar la respectiva secuencia de salidas e instantes en que se cargará la batería de cada bus con el propósito de atender el plan de salidas propuesto inicialmente.

Keywords: Ciudades inteligentes, buses eléctricos, programación estocástica multietapa, problema de programación de vehículos con múltiples almacenes.

1. Introducción

Aspectos tan importantes como la sustentabilidad y la reducción en las emisiones de gases con efecto invernadero están presentes en el diseño y funcionamiento de los actuales sistemas de transporte público. En este sentido, tanto en Europa como en Asia ya operan buses eléctricos desde hace algunos años, y, en el caso específico de Santiago de Chile, esto ocurre desde marzo de 2019 [1]. Es más, a finales del año 2019, Santiago se consolidó como la segunda ciudad del mundo con más buses eléctricos, con un total de 386 buses [2]. Asimismo, en junio del presente año, el Ministerio de Transporte y Telecomunicaciones de Chile anunció que se espera duplicar prontamente la flota actual, llegando a disponer en un breve plazo de 776 vehículos eléctricos [3]. Con estos buses no solo se busca disminuir las emisiones de CO_2 del sistema, sino también mejorar la calidad del servicio, pues estos poseen aire acondicionado, espacios para cargar dispositivos eléctricos, etc. Sin embargo, su empleo también plantea desafíos operacionales al momento de satisfacer el cumplimiento de salidas programadas, ya que su despacho debe tomar en cuenta el nivel de la batería y programar sus respectivas

cargas frecuentemente. Lo anterior, sumado a la incertidumbre de las condiciones de tráfico durante el día, generan antecedentes a tomar en cuenta en el despacho de los buses eléctricos.

En [4] se detalla el problema de la programación de vehículos convencionales (VSP por sus siglas en inglés), en donde se presentan los distintos antecedentes asociados a este problema, tipos de programación de vehículos y sus variaciones. Sin embargo, no se tratan buses eléctricos, ni aspectos estocásticos en los modelos presentados, a diferencia del problema que aborda el presente trabajo.

Con respecto a las variaciones en el modelo base en vehículos convencionales, [5] estudia el problema en ciudades grandes que poseen múltiples almacenes de buses. Para abordar este problema generalmente se tiende a descomponerlo en problemas de programación (scheduling) para cada uno de estos almacenes tratados individualmente. El modelo propuesto es utilizado en un día completo de operación subdividido en mañana, tarde y noche y resuelto a través de una heurística ad–hoc.

En [6] se aborda el despacho de buses eléctricos sin considerar cambio de batería, contemplando una discretización de los niveles de batería para decidir cuántos viajes hará el bus antes de tener que volver al terminal a realizar una carga. Los autores resuelven cuatro instancias de su modelo, donde las primeras dos son de pequeño y mediano tamaño y fueron resueltas a través de un modelo de programación lineal entera. Las otras dos fueron resueltas mediante generación de columnas. Cabe mencionar que estos autores no consideran comportamientos estocásticos en su modelo.

Por otra parte, en [7] se considera una flota con buses eléctricos e híbridos, en donde dada una programación inicial de salidas, se busca el despacho óptimo de buses, logrando con esta mezcla de flota reducir los problemas de carga de batería. Cabe mencionar que en este problema se atienden varias líneas de servicio, pero todos los buses comienzan su recorrido desde un almacén en común. El modelo presentado corresponde a un MIP y no se consideran aspectos bajo incertidumbre.

En [8] se propone un modelo dinámico con estrategias robustas que considera aleatoriedad en las condiciones de viajes para la programación de despacho de buses eléctricos. En particular, la representación de la red, tanto en el modelo determinista como en su versión estocástica, se realiza a través de nodos *time span*, es decir, cada viaje, estación de carga y almacén de bus es representado por su respectivo nodo y tiene asignado un intervalo de tiempo. Cabe mencionar que el problema estudiado se formula considerando un solo almacén de buses, y tanto un modelo determinista como uno estocástico que son lineales en variables entera–mixta y que se resuelven a través de estrategias tales como: path–based formulation, Branch–and–price y initial path set generation.

En el presente artículo se aborda un problema con múltiples almacenes de buses eléctricos y condiciones de tráfico estocásticas, en el cual la representación de la red es *time–expanded* (a través de nodos *time span*) y se formula un modelo de optimización estocástica con recurso de múltiples etapas. Por lo que sabemos hasta el momento, no existen trabajos que abarquen estos temas en conjunto.

En lo que sigue del artículo, la sección 2 describe los principales antecedentes del problema y el modelo de optimización estocástica propuesto. La sección 3 describe antecedentes del caso de estudio abordado y los resultado preliminares alcanzados. Por último, la sección 4 da cuenta de las conclusiones alcanzadas y el trabajo futuro a desarrollar.

2. Metodología

El problema abordado consiste en la programación de despachos de buses eléctricos bajo condiciones de tráfico estocásticas y considera la programación detallada de la salidas y de la carga de batería de cada bus en cada almacén. Un aspecto importante del problema comprende entonces la variabilidad observada en los tiempos de viaje, haciendo necesaria la incorporación explícita de este antecedente bajo incertidumbre en un modelo de toma de decisiones para el problema. Bajo el nombre de Programación Estocástica se reúne una parte importante de la literatura de modelos de optimización bajo incertidumbre, que a través de los modelos con recurso permite considerar la inclusión de diversos escenarios posibles para un antecedente como el señalado. Estos modelos con recurso extienden los modelos deterministas de Programación Matemática al incluir explícitamente variables aleatorias en los parámetros del modelo. En particular, un modelo con recurso en Dos Etapas provee una solución óptima en la cual hay variables de decisión, llamadas here–and–now, cuyo valor es previo e independiente a la realización del parámetro aleatorio y variables de decisión llamadas de recurso (por escenario), cuyo valor se adopta en respuesta a la decisión de la variable here–and–now y de una realización específica de la variable aleatoria (escenario), lo cual permite dar la flexibilidad necesaria al modelo propuesto. En este trabajo, como en muchos otros, las decisiones se toman sobre múltiples intervalos de tiempo y el valor de los parámetros aleatorios cambia con una dependencia intertemporal, dando origen a un modelo con recurso de Múltiples Etapas que extienden el anterior, ver por ejemplo [9].

Así, el modelo propuesto en este trabajo abordará la operación de un intervalo de tiempo, el cual será subdividido a su vez en múltiples etapas (de tiempo) según el comportamiento de los tiempos de viaje estocásticos. Para entender mejor el modelo estocástico con recursos de múltiples etapas propuesto, definimos previamente lo que entendemos por etapa, estado y escenario.

a) **Etapas**. Se tomará una franja horaria de un día de operación, y esta franja se subdividirá en distintos intervalos de tiempo que definen las etapas del modelo, en cada una de las cuales se deberá tomar la decisión de qué bus realizará la salida programada, tomando en cuenta la información de las etapas anteriores y la definición del parámetro asociado al tiempo de viaje en esa etapa.
b) **Estados**. Como ya se ha señalado, en este modelo, el parámetro bajo incertidumbre es en el tiempo de viaje de los buses eléctricos, y para ello este parámetro es modelado como un número finito y discreto de estados, en

donde cada uno tiene asociado una probabilidad condicional de ocurrencia definida para cada etapa en que se ha subdivido el horizonte de planificación.

c) **Escenarios**: Un escenario corresponde a la defínción de una serie de estados desde la primera hasta la última etapa. Para entenderlo mejor, esto puede ser representado como un "árbol", en donde cada estado es la ramificación de un nodo, y un escenario correspondería a algún camino desde el primer nodo en el "árbol" hasta un nodo en la última etapa. La probabilidad de ocurrencia de cada escenario corresponde a la probabilidad condicional de que ocurran todos los estados pertenecientes a dicho escenario.

Para ejemplificar lo anterior, se presenta un árbol de escenario en la Figura 1, en donde existen tres etapas. Utilizando este ejemplo para el problema en cuestión, a cada etapa puede pertenecer un número finito de viajes. En el primer nodo los buses que atenderán las salidas programadas se deben adoptar independientemente de los tiempos de viaje, mientras que las decisiones pertenecientes a la segunda etapa presentan dos tipos de estados (podría ser uno pesimista y otro optimista) en los tiempos de viaje resultante de los buses disponibles para el despacho, y a su vez, estos se vuelven a ramificar en dos estados, dando origen así a la tercera etapa. Cada una de estas ramificaciones tiene asignada una probabilidad, en donde en cada etapa, la suma de las probabilidades de ocurrencia de todos los estados en dicha etapa debe sumar 1. Respecto a los escenarios, en este ejemplo se pueden apreciar cuatro escenarios, los cuales corresponden a los cuatro posibles caminos desde el nodo 1 hasta los nodos 4, 5, 6 y 7. Cabe mencionar que, la suma de la probabilidad de ocurrencia de todos los escenarios debe ser igual a 1.

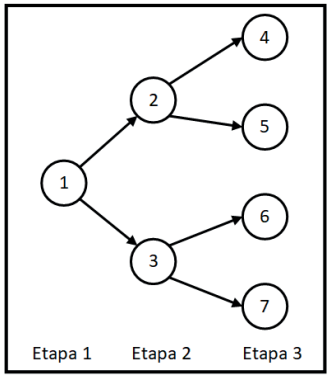

Figura 1: Árbol de escenarios con 3 etapas.

Motivado por el problema que enfrenta una empresa del transporte público de la ciudad de Santiago de Chile, los principales supuestos considerados en la formulación del modelo son los siguientes:

- Viajes tipo *deadhead trip* (viajes sin pasajeros) no están permitidos.

- Existe un solo tipo de cargadores.
- No está permitido el cambio de batería.
- La flota está conformada solo por buses eléctricos.
- Si un bus visita una estación de carga, este estará ahí un tiempo fijo cargando su batería independiente del nivel de carga.

El problema a su vez es representado mediante un grafo $G = (N, A)$, donde N representa el conjunto de nodos y A el conjunto de arcos. N está conformado por el nodo de "origen" o_k; el nodo de "término"d_k de cada almacén de buses eléctrico k (estos dos nodos se encuentran en el mismo lugar físico, es decir, ambos hacen referencia al almacén k); el conjunto de viajes I, en el cual están considerados todos los viajes de los k almacenes, cada uno de estos con un horario de salida ya programado y tiempos de viaje estocásticos que deben ser atendidos una sola vez y por un solo bus; y el conjunto de nodos virtuales V^k, los cuales se encuentran en los almacenes, pero se distinguen de o_k y d_k en el sentido de facilitar el modelamiento. Estos nodos virtuales se dividen a su vez en V_1^k y V_2^k, donde el primero permite representar un bus eléctrico que se dirige al almacén de buses, carga su batería y luego continúa con la secuencia de viajes, mientras que el segundo permite representar cuando un bus eléctrico va al almacén de buses, no carga su batería y espera simplemente para luego continuar con la secuencia de viajes. Cabe mencionar que estos nodos son denominados nodos *time span*, es decir, no solamente se encuentran en un punto espacial, sino que también temporal, por lo que cada nodo tiene asignado un intervalo de tiempo y así la red completa resulta ser una red *time–expanded*.

Los conjuntos, parámetros y variables de decisión del modelo se describen a continuación:

Conjuntos
S : Conjunto de escenarios.
K : Conjunto de almacenes de buses eléctricos.
A_s^k : Conjunto de arcos del almacén k bajo el escenario s.
N^k : Conjunto de nodos del almacén k.
I : Conjunto de viajes que hay que atender.
V^k : Conjunto de nodos virtuales del terminal k, los cuales se dividen en V_1^k y V_2^k .
V_1^k : Buses que llegan al almacén k, cargan batería, y luego salen a seguir atendiendo la secuencia de viajes.
V_2^k : Buses que llegan al almacén k, no cargan batería, y luego en algún momento vuelven a seguir atendiendo la secuencia de viajes.
W_j : Conjunto de nodos que si al finalizar un viaje deciden cargar su batería (V_1^k), coinciden con parte del tiempo de carga del bus que luego de realizar el viaje j decidió cargar su batería.

El primer conjunto corresponde a los escenarios posibles del modelo estocástico multi–etapa. El segundo está vinculado con todos los almacenes de buses eléctricos. El tercer conjunto hace referencia a los arcos admisibles que se logran desde cada terminal, bajo un cierto escenario, es decir, la conexión entre un viaje

y otro o entre un viaje y un almacén de bus (ya sea parar iniciar su viaje, cargar batería, esperar o retornar al almacén una vez terminada la secuencia de viajes). El siguiente conjunto corresponde a los nodos de la red, es decir, los viajes, el nodo de origen y nodo destino final de cada almacén y nodos virtuales. El quinto conjunto son todos los viajes que se deben atender. Luego, vienen los conjuntos de nodos virtuales, los cuales hacen referencia a un viaje al almacén para seguir atendiendo futuros viajes de su secuencia. Por último, está el conjunto de nodos que deciden cargar su batería y coinciden con parte del tiempo de carga de batería del bus que realizó anteriormente el viaje j.

Parámetros

$e_{i,j}$: Consumo de batería desde el nodo i al nodo j.
W : Porcentaje de batería que se carga en una estación.
r^k : Cantidad de vehículos en el almacén k.
E_{max} : Máximo nivel de batería permitido.
E_{min} : Mínimo nivel de batería permitido.
Cr^k : Cantidad de estaciones de carga disponibles en el almacén k.
M : Penalización por no atender un viaje.
p_s : Probabilidad de que ocurra el escenario s.
c_{ij} : Costos operacionales por realizar el recorrido por el arco (i, j).

Cabe mencionar que los costos operacionales consideran el tiempo ocioso del bus eléctrico cuando espera en el terminal (V_2^k), el costo de cargar batería en el terminal (V_1^k) y un costo fijo por uso de vehículo, es decir, por sacar un bus eléctrico del almacén para que sea utilizado en atender los viajes requeridos.

Variables de decisión

$x^k_{i,j,s}$: Variable binaria que vale 1 si el bus del almacén k, bajo el escenario s, realiza el viaje al nodo j luego de haber realizado el viaje al nodo i y 0 si no.
$z^k_{i,j,s}$: Variable binaria que vale 1 si el bus del almacén k, bajo el escenario s, **no** realiza el viaje al nodo j luego de haber realizado el viaje al nodo i y 0 si no.
$g_{j,s}$: Variable real que indica el consumo de batería acumulado del bus al terminar el viaje al nodo j bajo el escenario s.
$Aux1^k_{i,j,s}$: Variable auxiliar real.
$Aux2^k_{i,j,s}$: Variable auxiliar real.

La primera variable de decisión mostrada tiene como finalidad escoger la secuencia de viajes que realizará cada bus eléctrico. La segunda variable de decisión corresponde a si se decide no atender un viaje en particular debido a que no es posible. Cabe mencionar que esta última permitiría saber qué viajes necesitarán el apoyo de otro bus adicional para así lograr atender todos los viajes. La variable $g_{j,s}$ sirve para llevar un recuento de la batería consumida por cada bus mientras realiza su secuencia de viajes. Por último, las dos variables auxiliares serán utilizadas para tener una representación lineal de las restricciones

relacionadas con el consumo acumulado de batería.

$$\text{mín} \quad \sum_{s\in S} p_s \left[\sum_{k\in K} \sum_{(i,j)\in A_s^k} c_{i,j} x_{i,j,s}^k + \sum_{k\in K} \sum_{(i,j)\in A_s^k} M z_{i,j,s}^k \right] \tag{1}$$

s.a

$$\sum_{i:(i,j)\in A_s^k} (x_{i,j,s}^k + z_{i,j,s}^k) = 1, \quad \forall j \in I, \forall k \in K, \forall s \in S \tag{2}$$

$$\sum_{j:(o_k,j)\in A_s^k} x_{o_k,j,s}^k \leq r^k, \quad \forall k \in K, \forall s \in S \tag{3}$$

$$\sum_{i:(i,j)\in A_s^k} x_{i,j,s}^k - \sum_{p:(j,p)\in A_s^k} x_{j,p,s}^k = 0, \quad \forall j \in I \cup V_1^k \cup V_2^k, \forall k \in K, \forall s \in S \tag{4}$$

$$g_{j,s} = \sum_{i:(i,j)\in A_s^k} (Aux1_{i,j,s}^k + e_{i,j} \cdot x_{i,j,s}^k), \quad \forall j \in I \cup V_2^k, \forall k \in K, \forall s \in S \tag{5}$$

$$Aux1_{i,j,s}^k \leq E_{max} \cdot x_{i,j,s}^k, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{6}$$

$$Aux1_{i,j,s}^k \leq g_{i,s}, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{7}$$

$$Aux1_{i,j,s}^k \geq g_{i,s} - (1 - x_{i,j,s}^k) \cdot E_{max}, \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{8}$$

$$g_{j,s} = \sum_{i:(i,j)\in A_s^k} (Aux2_{i,j,s}^k - W \cdot x_{i,j,s}^k), \quad \forall j \in V_1^k, \forall k \in K, \forall s \in S \tag{9}$$

$$Aux2_{i,j,s}^k \leq E_{max} \cdot x_{i,j,s}^k, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{10}$$

$$Aux2_{i,j,s}^k \leq g_{i,s}, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{11}$$

$$Aux2_{i,j,s}^k \geq g_{i,s} - (1 - x_{i,j,s}^k) \cdot E_{max}, \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{12}$$

$$g_{i,s} + \sum_{j:(i,j)\in A_s^k} e_{i,}j \cdot x_{i,j,s}^k \leq (1 - E_{min}), \quad \forall i \in I, \forall k \in K, \forall s \in S \tag{13}$$

$$\sum_{j:(j,r)\in A_s^k} x_{j,r,s}^k + \sum_{w\in W_j} \sum_{i\in I} x_{i,w,s}^k \leq C r^k, \quad \forall r \in V_1^k, \forall k \in K, \forall s \in S \tag{14}$$

$$x_{i,j,s}^k \in \{0,1\}, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{15}$$

$$z_{i,j,s}^k \in \{0,1\}, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{16}$$

$$Aux1_{i,j,s}^k \geq 0, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{17}$$

$$Aux2_{i,j,s}^k \geq 0, \quad \forall i \in N^k, \forall j \in N^k, \forall k \in K, \forall s \in S \tag{18}$$

$$g_{j,s} \geq 0, \quad j \in I \cup V_1^1 \cup V_1^2, \forall s \in S \tag{19}$$

$$\textit{Restricciones de no anticipatividad} \tag{20}$$

La función objetivo (1) minimiza los costos totales de la programación realizada en el uso de vehículos y carga de batería, incluyendo un término que penaliza los viajes no atendidos. Respecto a las restricciones del modelo, la restricción (2) asegura que cada viaje debe ser atendido una vez, ya sea por la

flota de buses disponible o por algún bus de apoyo en la práctica ($z^k_{i,j,s}$). La restricción (3) asegura que no se pueden utilizar más buses eléctricos de los disponibles en cada almacén de buses. La restricción (4) asegura la conservación de flota de buses. La restricción (5) permite calcular el consumo acumulado de energía del bus al realizar un viaje del nodo i al nodo j bajo el escenario s. Las restricciones (6)–(8) representan una linealización de la ecuación no–lineal $g_{j,s} = \sum_{i:(i,j)\in A^k_s} (g_i + e_{i,j}) \cdot x^k_{i,j,s}$, cuya representación lineal es la ecuación anterior. De igual manera la restricción (9) actualiza el consumo acumulado de energía del bus eléctrico cuando este carga su batería, y al igual que la restricción (5), esta restricción se debe linealizar y para ello se utilizan las restricciones (10)–(12) conjuntamente con una variable auxiliar ($Aux2^k_{i,j,s}$). La restricción (13) no permite que un bus eléctrico atienda un viaje si su porcentaje de batería es menor al porcentaje mínimo necesario para abandonar el almacén de buses. La restricción (14) asegura que la cantidad de buses que visiten la estación de carga del almacén k no exceda su capacidad. Las restricciones (15)-(19) muestran la naturaleza de las variables de decisión. Por último, las restricciones (20) son esenciales para los modelos estocásticos con escenarios, ya que aseguran que las decisiones en un nodo deben ser iguales, es decir, si tomamos como ejemplo la Figura 1, correspondería a un caso de 4 escenarios y 3 etapas, entonces, si uno tomara todos los viajes correspondientes al nodo 1, se tendría las mismas decisiones de ese nodo en todos los escenarios. Del mismo modo, si tomamos el nodo 2 de la segunda etapa, las decisiones tomadas en ese nodo deben ser las mismas para el escenario 1-2-4 y para el escenario 1-2-5. En el contexto del problema, las decisiones corresponden al arco (i, j) a recorrer por el bus eléctrico.

El modelo resultante corresponde a un modelo lineal de optimización estocástica de múltiples etapas en variables entera–mixta. En la siguiente sección se describe un caso de estudio preliminar a partir de la problemática que define el despacho de un recorrido de buses eléctricos de una empresa del transporte público de Santiago.

3. Caso de estudio

3.1. Análisis estadístico

En esta sección se estudia una instancia utilizando información real de la operación durante meses normales del año 2019 de una línea de recorrido de bus eléctrico del transporte público de la ciudad de Santiago de Chile. En primer lugar, se realizaron diferentes test de ajuste de distribución de probabilidades de Kolmogórov-Smirnov a los tiempos de viajes de todo un día y para intervalos de tiempo, obteniendo por ejemplo que la mejor distribución es una distribución normal con datos de todo un día, ver Figura 2.
Luego, se agruparon los días de la semana de acuerdo a comportamientos similares. De esta forma, la semana se dividió en 3 grupos: lunes–martes–miércoles, jueves–viernes y sábado–domingo.

Ante la variabilidad observada, la Tabla 1 permite apreciar los tiempos esperados y la desviación estándar de distintas zonas horarias de los días sábados y

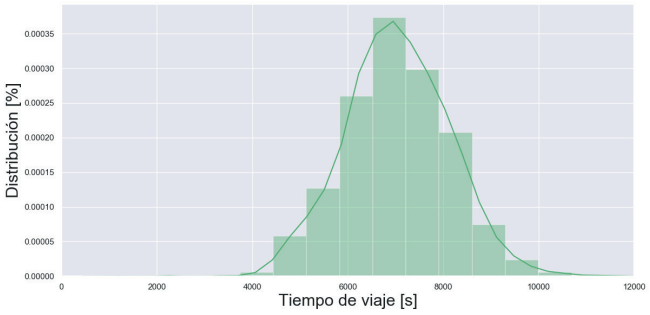

Figura 2: Ajuste de distribución a los tiempos de viajes.

domingos. Cabe mencionar que en el fin de semana no hay registro entre las 00:01 y las 08:00 debido a que en ese horario la empresa utiliza buses convencionales.

Tabla 1: Tiempos medios y desviación estándar de distintas zonas horarias.

Zona horaria	Media $[HH:MM:SS]$	Desv Estándar $[HH:MM:SS]$
8:00 - 12:00	1:46:33	0:14:37
12:00 - 17:15	1:53:41	0:14:25
17:15 - 22:15	1:44:08	0:10:58
22:15 - 00:00	1:27:21	0:17:43

Del mismo modo, el caso de estudio se realiza en un día sábado, específicamente en la zona horaria $12:00-17:15$, en la cual se vuelven a calcular los tiempos medios y desviaciones estándar dentro de la misma zona horaria con intervalos de tiempos cada 15 minutos, para así poder separar, dentro de esta zona horaria, el problema en múltiples etapas.

En esta instancia preliminar se utilizan 2 almacenes de buses, en donde cada uno de ellos debe atender 22 viajes (44 viajes en total), los cuales tienen una frecuencia de salida cada 15 minutos. Además, se cuenta con 11 buses y 7 estaciones de carga en cada almacén. Se considera como supuesto que todos los buses a utilizar comienzan con 100 % de su batería cargada y que no es posible que el bus atienda un viaje si su nivel de batería es menor al 30 %. El problema es dividido en 3 etapas, en donde los primeros 3 viajes de cada almacén pertenecen a la primera etapa, los siguientes 6 viajes a la segunda etapa y el resto a la tercera etapa. Se consideró, para cada etapa, un estado optimista y otro pesimista de acuerdo a la desviación estándar de cada etapa, generando así 4 escenarios que forman un árbol de escenarios como el mostrado en la Figura 1.

La probabilidad de ocurrencia de cada estado es del 50 %, y los viajes que se encuentran en la primera etapa tienen tiempos de viajes deterministas.

3.2. Resultados Computacionales

La información de la cantidad de viajes y las respectivas salidas de estos, para cada uno de los almacenes de buses eléctricos, se encuentran en un archivo Excel. Luego, a través de Python 3.7 se realiza el procesamiento de datos para formar la red *time-expanded* y entregar toda esta información al modelo formulado en Pyomo. El modelo fue resuelto con el solver Gurobi 9.0.2 en un computador con un procesador Intel Core i5 de 1.60[GHz] y 8[Gb] de RAM. El tiempo de ejecución de la instancia resuelta fue de 15,3 segundos.

El modelo resuelto entrega, para cada escenario, la secuencia que debe seguir cada bus, y los viajes que no se pueden atender por falta de flota, en donde la penalidad de esta último asciende a un valor del orden de $\$10^6$. Por otra parte, los costos operacionales son del orden de $\$10^3$.

El valor de la función objetivo en este modelo (conocido como *Recourse Problem* en la literatura) resulta ser de $17.620.764, y para medir la calidad e importancia de esta, es necesario analizar ciertos indicadores que son comunes en problemas estocásticos, tales como:

- EVPI (*Expected value of perfect information*): Representa la máxima cantidad que el tomador de decisiones está dispuesto a pagar por contar con toda la información acerca del futuro, y se calcula como la diferencia entre el *Recourse Problem* (RP por sus siglas en ingles) y el promedio del óptimo de cada escenario resuelto por separado (conocido como *Wait-and-see*).
- VSS (*Value of stochastic solution*): Muestra el verdadero aporte del modelo estocástico comparado con la calidad de la solución resultante de un modelo determinista subyacente. Para este indicador es necesario calcular previamente el *Expected result of using the EV solution*, el cual corresponde a resolver el modelo determinista usando como instancia el promedio de los parámetros con incertidumbre de los escenarios (EV), y luego tomar las decisiones de primera etapa realizadas y fijarlas en el modelo estocástico con recursos. Este resultado se conoce como EEV, y la diferencia del RP con el EEV corresponde al VSS, el cual permite cuantificar el valor que tiene el modelo estocástico.

Para este caso de estudio, el valor del *Wait-and-see* resultó ser $12.916.522, mientras que el EV de $12.126.022 y el EEV de $20.620.764. Asimismo, se tiene que la cota inferior y superior del RP es el *Wait-and-see* y el EEV, respectivamente.

En la Tabla 2 se muestran los valores de los indicadores mencionados anteriormente.

Tabla 2: Valores de indicadores.

Indicador	**Valor**
EVPI	$ 4.704.242
VSS	$ 3.000.000

Se puede apreciar, en primer lugar, que ambos indicadores representan un valor cercano al 30 % y al 20 % del valor del modelo con recurso, respectivamente. Ahora bien, el resultado del EVPI, quiere decir que el tomador de decisiones está dispuesto a pagar como máximo $ 4.704.242 por contar con información sobre el futuro, mientras que el VSS muestra que existe una gran ganancia al usar el modelo estocástico frente al determinista para el escenarios promedio, lo cual da relevancia al uso de la metodología propuesta.

4. Conclusiones y trabajos futuros

En este trabajo se formula un modelo de optimización estocástica multi–etapa para la programación de salidas de flotas de buses eléctricos con múltiples almacenes de buses, donde se considera como parámetro bajo incertidumbre el tiempo de viaje ante las condiciones de tráfico. Asimismo, el modelo emplea una representación de la red a través de nodos *time–expanded*, lo cual no es muy común en la literatura para este tipo de problema. Hasta donde sabemos, no hay evidencia de trabajos que abarquen todos los aspectos considerados. Adicionalmente, analizamos la información de operación en meses normales del año 2019 de una línea de buses eléctricos del transporte público de la ciudad de Santiago de Chile, y se determinó que la distribución que mejor se ajustaba a los tiempos de viajes es la distribución normal. Luego, se dividieron los días de la semana en tres grupos que compartían comportamientos similares dentro de ciertas franjas horarias, por lo que así se pudo dividir el día completo de operación, de los días pertenecientes a estos grupos, en varias franjas horarias.

Se resolvió una instancia utilizando la información de operación de un día sábado. Esta instancia fue resuelta para una de esas franjas con un modelo de optimización estocástica con recurso de tres etapas con 4 escenarios. El solver seleccionado logra resolver esta instancia en alrededor de 15 segundos. Para poder medir la calidad de la solución estocástica (RP), se calculó los valores *Wait-and-see*, EEV y EV, los cuales fueron usados para calcular los indicadores EVPI y VSS. El primer indicador muestra la máxima disposición a pagar por el tomador de decisión por contar con información sobre el futuro, mientras que el VSS muestra que existe una gran ganancia al usar el modelo estocástico frente al determinista en escenarios con incertidumbre. Ambos indicadores alcanzaron valores altos en términos relativos, por lo que se concluye que este modelo de optimización estocástico tendría un gran impacto al ser utilizado en este problema.

Como trabajo futuro, se espera agregar al modelo cierta flexibilidad en el despacho lo que permitirá eventuales retrasos en las salidas, con su correspondiente penalización por minuto de retraso. Del mismo modo, agregar más de un recorrido de bus eléctrico, y realizar este modelamiento de múltiples etapas con más de una zona horaria. Respecto a los tiempos de resolución, hasta el momento no parecen ser muy elevados, pero si al agregar estos nuevos aspectos los tiempos de resolución aumentan considerablemente, será necesario evaluar un método de resolución algorítmico.

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Filosofia *Lean* em ambientes acadêmicos: Um estudo de caso em uma organização de nível técnico

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Resumo. Apesar do seu surgimento ter ocorrido no meio industrial, atualmente, a filosofia *Lean* pode ser encontrada em diversas áreas da sociedade. Inicialmente, *Lean* Manufacturing, era visto como uma iniciativa que buscava eliminar desperdícios. Com a sua disseminação em outras áreas como serviços, engenharia, militar e saúde, percebe-se que essa filosofia possui um potencial relevante, podendo ser utilizada em qualquer tipo de atividade ou organização. O objetivo deste estudo foi aplicar os conceitos *Lean* em organizações escolares. Os passos metodológicos utilizados podem ser descritos pela capacitação da equipe, identificação dos principais desperdícios encontrados através da análise dos processos, elaboração e implementação de uma proposta de melhorias. O estudo caracteriza-se como um estudo de caso, que ocorreu em uma organização de nível técnico privado entre os meses de outubro de 2019 e março de 2020. Como resultados destacam-se a redução no volume de material impresso, redução no consumo de insumos em exercícios práticos, redução no tempo de atendimento e de feedback e engajamento da equipe de trabalho nos processos de melhoria. Os resultados do estudo demonstram a aceitação e potencialidade do *Lean* como uma ferramenta de melhoria apresentando sua contribuição em diversas áreas. Como destaque, elenca-se a redução com energia elétrica, água e insumos diretamente ligados as atividades educacionais realizadas em laboratório.

Palavras-chave: *Lean*, Educação, Aplicabilidade, Ensino Básico, Ensino técnico.

1 Introdução

A educação é vista como um fator importante na evolução da sociedade. Nos últimos anos começou a mostrar sinais de estagnação, e observou-se um declínio no apoio financeiro do governo à educação [1].

A atenção às análises de custo-efetividade e custo-benefício aumentou, aos países está sendo solicitado realizar mais com os mesmos recursos, ou ainda menos, devido às tendências econômicas descendentes da última década [1,2]. As instituições educacionais, consequentemente, concentraram-se na redução de custos e no aumento da eficiência e, ao mesmo tempo, trabalharam para atender ou mesmo superar as expectativas [1,3].

Os princípios e práticas *Lean* foram incorporados em todo o mundo em organizações do setor público e privado, sendo desenvolvidas ao longo de várias décadas, objetivando estabelecer a excelência operacional como estratégia. *Lean* é um termo utilizado para denominar uma filosofia de negócios fundamentada nos princípios iniciais do Sistema Toyota de Produção. Busca a melhoria contínua visando a eliminação de desperdícios que não agregam valor ao produto final [4]. É importante entender que os conceitos e técnicas do *Lean* devem ser adequados aos ambientes de ensino.

Os primeiros registros de implementação *Lean* em ambientes educacionais surgiram no início dos anos 2000 [5], e nos últimos anos demonstram uma tendência de crescimento [6].

Danese *et al*.[7] destaca que embora a implementação dos conceitos *Lean* estejam sendo cada vez mais aplicados, e os registros de casos bem sucedidos apareçam a todo momento, a literatura sobre *Lean* implementado em instituições educacionais ainda dá seus primeiros passos. Grande parte das pesquisas publicadas destacam a aplicação do pensamento enxuto no ensino superior, classificado como *Lean Higher Education* (LHE) [8]. Sendo assim, encontra-se na literatura uma lacuna quanto a sua aplicação em instituições de nível básico e técnico.

O objetivo deste estudo foi aplicar os conceitos *Lean* em uma organização escolar de nível técnico, através de um estudo de caso, identificando os principais desperdícios por meio da avalição dos processos, elaboração e implementação de uma proposta de melhoria subdividida em 6 etapas, com o propósito de reduzi-los, visto que, a eliminação de desperdícios é a prioridade da filosofia *Lean*, em busca de altos padrões de eficiência.

2 Referencial Teórico

Lean é um termo utilizado para denominar uma filosofia de gestão fundamentada no Sistema Toyota de Produção, que busca olhar atentamente as atividades básicas de um negócio e identificar o que é desperdício e o que é o valor a partir da ótica dos clientes usuários.

O Sistema Toyota de Produção surgiu logo após a Primeira Guerra Mundial, mudando o sistema de produção artesanal para a produção em massa [9]. A produção em massa tradicional era composta pelo sistema de Taylor, agrupado a inovações de manufatura desenvolvidas por Ford e de técnicas de administração e *marketing* de Sloan, onde grupos organizados de trabalhadores que controlavam tarefas e funções no trabalho, sendo este sistema, vitorioso por décadas [10].

Logo após a Segunda Guerra Mundial, Eiji Toyoda e Taichi Ohno, da Toyota japonesa aproveitaram o momento de dificuldades na indústria automobilística, para desenvolver o modelo de produção enxuta, sendo que este conceito emprega as vantagens de produção de ambos os modelos (artesanal e em massa), mas, evita os altos custos do primeiro modelo bem como a rigidez do segundo modelo [11]

Sistema *Lean* é descrito como a integração de princípios, técnicas operacionais e ferramentas que levam a incessante busca pela perfeição para a criação de valor ao cliente, tornando as empresas mais eficientes, competitivas, reduzindo custos, melhorando a qualidade e aumentando a satisfação do cliente [12].

O *Lean* busca a eliminação de desperdícios nas organizações, seja nas operações, tarefas, tempo, energia, dinheiro ou de materiais, diretamente vinculada a qualidade total e requer um grande envolvimento dos funcionários em todos os níveis de decisão. Os trabalhadores multifuncionais e com autonomia na tomada de decisões são na produção enxuta peças fundamentais [13,14].

O *Lean* é baseado em cinco princípios fundamentais, na premissa de que as organizações são compostas de processos [15]. Esses são:

I. Especificação de valor do ponto de vista do cliente;

II. Identificação do fluxo de valor para cada produto e eliminação das etapas que não criam valor;

III. Fluidez do produto de forma suave e contínua pelo fluxo de valor;

IV. Onde o fluxo contínuo não é possível, é necessário permitir que os clientes obtenham o valor entre todas as etapas;

V. Apontar para um estado de perfeição, reduzindo o número de etapas e o tempo necessário para atender o cliente [11].

Ainda, Arboleda [16], define *Lean* como uma filosofia de gestão que melhora os processos produtivos pela eliminação de todos os tipos de desperdícios, obtendo como resultados a efetividade e a agilidade, propiciando que a empresa se torne competitiva no mercado. De acordo com os proponentes dos princípios *Lean*, embora essas definições possam variar por setor, todas elas são encontradas de alguma forma em todos os tipos de organização.

Nesse sentido, surge o denominado *Lean Higher Education* (LHE), diante da necessidade de se adotar práticas e conceitos da produção *Lean* aos serviços administrativos, especificamente no que se refere aos serviços administrativos de instituições de ensino. Seu objetivo consiste na eliminação de passos e atividades desnecessárias que

sobrecarregam funcionários e não adicionam valor nos processos que devem beneficiar os estudantes, escolas e demais participantes [17].

Embora ainda haja um equívoco geral de que o *Lean* fornece ferramentas puramente de manufatura [18], os princípios *Lean* estão sendo cada vez mais usados em outros ambientes, como nas instituições de ensino superior para melhorar o processo [19]. Mesmo que se reconheça que exista diferença entre os resultados de um processo de fabricação e um serviço educacional, há uma sobreposição considerável em termos de sistemas de entrega [5].

Alguns fatores críticos podem ser identificados na implementação do *Lean* em instituições escolares de nível superior, o que tem se tornado um desafio para uma implementação de sucesso. Antony *et. al* [18] listou alguns desses desafios encontrados no momento de implementação:

- Problemas com terminologias vindas da indústria de fabricação para o setor de ensino;

- Desconforto no uso de ferramentas e técnicas que se mostraram eficazes nos setores de manufatura e serviços;

- Processos isolados e não em perspectiva de sistemas;

- Falta de consciência dos benefícios do *Lean* na indústria não-manufatureira;

- Falta de aceitação, apoio e comprometimento da equipe de gestão desde o início da iniciativa *Lean*, sem este envolvimento todo o esforço será absolutamente inútil;

- Visão de que a iniciativa *Lean* é uma solução rápida de corte de custos para atender *déficits* orçamentários, não alcançando os benefícios reais;

- Falta de pensamento do processo e propriedade do processo. Tudo é tratado como uma atividade ou tarefa ou procedimento, mas não como processo. O pensamento de processo não é prevalente em muitas instituições escolares e o estabelecimento de processos no local de trabalho requer uma mudança de mentalidade;

- Necessidade de definir e comunicar uma visão clara da cultura desejada no estabelecimento na busca de obter maior comprometimento organizacional;

- Falta de compreensão sobre os diversos tipos de clientes, dificultando o desenvolvimento de estratégias para atender as necessidades dos clientes;

- Pouco esforço no envolvimento da estratégia e aplicação do *Lean* por parte dos funcionários. É necessário conscientizar a real importância do esforço de cada um no momento de implementação;

- Falta de diversos recursos (tempo, orçamento, etc);

- Fraca ligação entre os projetos de melhoria contínua e os objetivos estratégicos das instituições.

A aplicação apropriada desta filosofia às instituições de ensino superior implica, assim, a busca de oportunidades para melhorar os processos, usando os princípios nas práticas diárias de gestão. Balzer [20] argumenta que o pensamento *Lean* pode auxiliar

as universidades na melhora contínua dos processos, fornecendo aos beneficiários o que eles esperam, ou seja, processos que respeitem a temporalidade, livres de erros, e que esteja disponível conforme a necessidade do beneficiário.

Portanto, para fornecer um fluxo contínuo baseado em altos padrões e eficiência, é importante definir claramente quais são os desperdícios e entender as relações entre eles para determinar as causas e, depois, encontrar métodos para eliminá-los. Os principais tipos de resíduos foram definidos como superprodução, espera, transporte, processos inadequados, inventário, movimentação, defeitos e comportamento. Precisa-se compreender que, os oito desperdícios citados anteriormente podem ser encontrados e definidos em qualquer tipo de organização, assim como nas organizações escolares.

No Tabela 1 são apresentados de forma comparativa dos oito desperdícios entre o *Lean manifaturing* e o *Lean Higher Education*.

Tabela 1: Comparativo desperdícios *Lean* (Fonte: autoria própria)

Desperdício	**Autor**	***Lean manufaturing***	**Autor**	***Lean Higher Education***
Superprodução	[21]	Produzir excessivamente ou cedo demais, resultando em um fluxo pobre de peças e informações, ou excesso de inventário;	[23,24]	Desenvolvimento de mais cursos do que o necessário; Produzindo mais do que o necessário para uso imediato. Carga de trabalho desequilibrada através semestres e programação irregular.
Espera	[21]	Longos períodos de ociosidade de pessoas, peças e informação, resultando em um fluxo pobre, bem como em lead times longos;	[23,24]	Atrasos na marcação do trabalho dos alunos; Fila para nada, à espera de documentos a serem aprovados, os sistemas de TI o tempo de inatividade, procurando arquivos, livros e documentos. Tempo necessário para responder a consultas de estudantes.
Transporte excessivo	[21]	Movimento excessivo de pessoas, informação ou peças resultando em dispêndio desnecessário de capital, tempo e energia;	[24]	O movimento de materiais tal como papel, múltiplos aprovações, múltiplas transferências. E-mail excessivo anexos.
Processos Inadequados	[21]	Utilização do jogo errado de ferramentas, sistemas ou procedimentos, ge-	[24]	Os funcionários não atuam em sua área de formação/ especialização.

		ralmente quando um processo mais simples pode ser mais efetivo;		
Inventário desnecessário	[21]	Armazenamento excessivo e falta de informação ou produtos, resultando em custos excessivos e baixa performance do serviço prestado ao cliente;	[24]	Mais suprimentos ou itens do que o necessário. Registros e documentos mantidos por mais tempo do que útil necessário.
Movimentação desnecessária	[21]	Desorganização do ambiente de trabalho, resultando baixa performance dos aspectos ergonômicos e perda frequente de itens.	[24]	O movimento desnecessário de funcionários e alunos. Departamentos espalhados por vários sites / campus.
Produtos Defeituosos	[21]	Problemas frequentes nas cartas de processo, problemas de qualidade do produto, ou baixa performance na entrega;	[23,24]	Observações evitáveis das atribuições; Erros na introdução de dados, salas de aula subutilizadas, erros de calendários.
Criatividade não utilizada dos funcionários	[22]	Indivíduos de alta capacidade realizando atividades de baixa capacidade.	[24]	Não usar habilidades completos das pessoas. Não dar às pessoas o direito de trabalhar

Sendo assim, o *Lean* é amplamente considerado em vários setores como a melhor prática para melhoria contínua, gerando interesse na educação sendo considerado um sistema de gestão organizacional muito útil [20]. O Sucesso de qualquer esforço organizacional, incluindo a aplicação do *Lean*, dependerá se a instituição está adequadamente preparada para implementar mudanças em todo o sistema.

3 Metodologia

3.1 Enquadramento metodológico da pesquisa

Este estudo, quanto a sua natureza é classificado como uma investigação aplicada que, de acordo com Prodanov & Freitas [25] tem por objetivo gerar conhecimentos para aplicação prática voltada a solução de problemas específicos, envolvendo verdades e interesses locais; sendo descritiva, pois seu objetivo é caracterizar os processos educacionais e expor como as tarefas são efetuadas, de acordo com o exposto por Gil [26] de que "as pesquisas descritivas têm como objetivo primordial a descrição das características de determinada população ou fenômeno".

Foi conduzido seguindo parâmetros de um estudo de caso simples, observando os processos da unidade em estudo e aplicando os conceitos do *Lean* para a observação

dos resultados. O estudo de caso, para Gil [27] trata de uma investigação empírica e compreende um método abrangente, utilizando-se da lógica do planejamento, coleta e análise de dados, visando uma investigação de um caso específico, delimitado e contextualizado em tempo e lugar.

Ainda Ventura [28] ressalta algumas das vantagens do estudo de caso como o estimulo a novas descobertas, em função da flexibilidade do planejamento, enfatizando a multiplicidade de dimensões de um problema, ainda apresenta geralmente simplicidade nos procedimentos, permitindo uma análise em profundidade dos processos e as relações entre eles.

Quanto a abordagem do problema, o processo da pesquisa caracteriza-se como quali-quantitativo [29]. Qualitativo, no que diz respeito a análise percepção dia/usuários em relação aos benefícios, bem como na elaboração e aplicação dos conceitos *Lean* e, quantitativo, quanto a mensuração dos resultados.

3.2 O estudo de caso

Com o propósito de avaliar as contribuições efetivas do *Lean Education*, os princípios e ferramentas de melhoria foram aplicadas em uma unidade educacional de ensino médio e técnico privado. A unidade em estudo funciona das 7:00 as 23:00 de segunda a sexta. Ao todo, cerca de 421 alunos estão matriculados de forma regular. Os cursos ofertados possuem carga horária mínima de 2 horas nas modalidades de aperfeiçoamento, os cursos de média ou longa duração possuem carga horária de 60 horas até 1600 horas.

Apesar da jovialidade das instalações, cerca de 3 anos, existem aspectos relatados pelos alunos passíveis de melhoria como: Demora no atendimento; ineficiência nos processos de organizações educacionais; excesso de burocracia; superprodução de materiais didáticos desatualizados; desorganização de ambientes e falta de informação e relação a programação das atividades.

Com o propósito de melhora na avaliação da instituição pelos discentes, foi iniciado o projeto de melhoria em outubro de 2019. A condução e aplicação do projeto foi dividido em etapas envolvendo cerca de 70% da equipe de profissionais da unidade educacional. A equipe inicial do projeto foi formada por técnicos de ensino, coordenadores pedagógicos, secretários, colaboradores do setor administrativo e colaboradores dos setores de limpeza e organização.

O projeto foi desenvolvido em seis etapas, conforme apresentado na Figura 1:

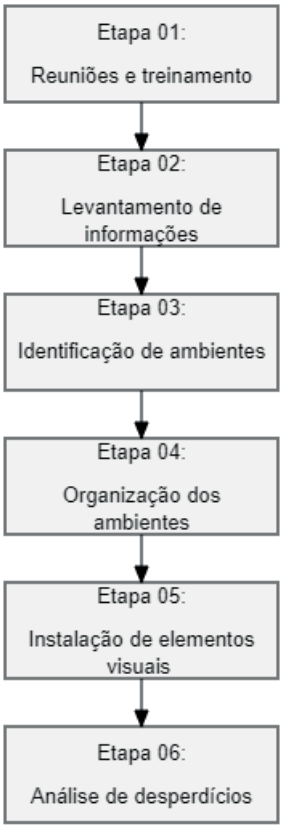

Figura 1: Etapas do estudo de caso (Fonte: Autoria própria)

A realização do estudo, utilizou como embasamento teórico da Tabela 1 com referência aos 8 desperdícios. A etapa 1 foi realizada por meio de reuniões e treinamentos da junto a equipe da unidade educacional. A etapa 2 foi realizada por meio do levantamento de informações. A etapa 3 correspondeu a identificação dos ambientes. A organização dos ambientes correspondeu a etapa 4. A etapa 5 foi realizada por meio da instalação de elementos de identificação visual. A etapa 6 correspondeu a identificação dos desperdícios.

4 Descrição do estudo de caso

Inicialmente, houve uma preocupação com a assimilação dos princípios e métodos utilizados pela filosofia *Lean* pelos colaboradores. Essa afirmação vai de encontro com a afirmação de Marvel e Standridge [30] quando os autores comentam que a implantação tradicional do *Lean* pode negligenciar a interação, variabilidade e dependências

peculiares ao ambiente em estudo. Frente a esta situação, as etapas iniciais propuseram a capacitação da equipe e análise dos ambientes em estudo.

A primeira etapa foi realizada por meio de reuniões e treinamento com os profissionais da unidade. Nessa etapa, o principal objetivo foi promover a conscientização e engajamento no projeto. Apesar do termo *Lean* ser novo para quase todos os integrantes a aceitação foi positiva. Um aspecto negativo dessa fase foi a ausência de alguns integrantes da alta administração. Cabe ressaltar que, apesar da provável contribuição, organizar momentos nos quais todos participantes pudessem participar, foi um grande desafio. Ao todo foram realizadas 6 reuniões com duração de 45 minutos. A Figura 2 apresenta as atividades desenvolvidas em cada uma das reuniões.

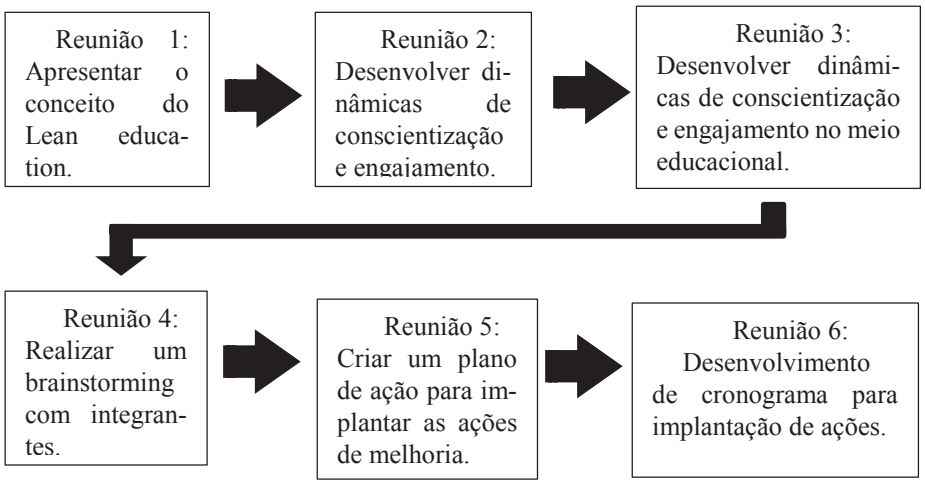

Figura 2: Assuntos tratados em cada reunião da Etapa 1 (Fonte: Autoria própria)

Ao final da primeira fase os princípios e contribuições do *Lean* já eram de domínio dos participantes. O cronograma inicial previu 3 meses de atividades encadeadas e dependentes nos laboratórios de práticas mecânicas e de modelagem computacional.

A segunda etapa foi realizada por meio da divisão dos integrantes em equipes para realização do levantamento de informações nos ambientes da unidade educacional. Cada equipe foi formada por um capitão e três outros colaboradores. Durante 15 dias as equipes analisaram os ambientes por meio de observações in loco e gravações de vídeo. Essa etapa evidenciou os potenciais da filosofia *Lean* em relação aos pontos de melhoria. Com o propósito aumentar a visão holística dos integrantes, as equipes foram, propositalmente responsabilizadas por ambientes que não faziam parte do seu dia-a-dia. Os principais pontos analisados nessa etapa foram: Espera; superprodução; Transporte excessivo; processos inadequados; Produtos ou serviços defeituosos; movimentação desnecessária e talentos não utilizados.

Ao final da segunda etapa, os problemas identificados foram compartilhados em uma sétima reunião. Os principais pontos elencados foram a movimentação excessiva

de técnicos em busca de materiais que estavam armazenados em outros ambientes; movimentação excessiva de alunos nos laboratórios ao longo do processo educativo em virtude da necessidade de ferramentas ou insumos; indisponibilidade de dados relacionados as atividades a serem desenvolvidas, necessidade de busca ou assinatura de documentos ou informações de posse da secretaria; desperdícios de água, luz e insumos pedagógicos; necessidade de organização diária ou a cada turno dos ambientes de aulas teóricas; falta de informações quanto ao respectivo ambiente de aula e a movimentação constante de profissionais na logística de materiais.

A terceira etapa teve como foco a identificação de pontos adequados para a instalação de placas ou murais. Complementando a terceira etapa, deu-se início a quarta etapa com a realização da organização das atividades para a promoção da organização dos ambientes. A quinta etapa do projeto foi desenvolvida com a criação de *tags* para instalação nas portas e marcação da posição do mobiliário no piso.

A sexta etapa foi realizada com o propósito de analisar desperdícios relacionados ao atendimento do público e solicitações de documentos. Para melhoria desse processo, foram instalados no hall de entrada, quadros informatizados com o ensalamento e o mapa de toda a unidade educacional. Outras ações foram desenvolvidas como a análise do sistema de iluminação e a sua adequação em relação ao horário de funcionamento. O desenvolvimento das etapas metodológicas promoveram melhorias e ganhos substanciais apresentadas na seção Discussão.

5 Resultados e discussões

Percebeu-se que a primeira etapa foi de extrema valia, pois possibilitou de forma organizada e clara, que todos os participantes tivessem o conhecimento necessário sobre a identificação e aplicabilidade da filosofia *Lean,* tendo interferência direta nos resultados da segunda etapa. A Tabela 2 apresenta os desperdícios identificados nos ambientes da unidade educacional utilizando como referência os oito desperdícios apresentados na Tabela 1.

Tabela 2: Identificação dos desperdícios (Fonte: Autoria própria)

Desperdício	Desperdício encontrado na organização
Superprodução	1 – Iluminação excessiva, 2 – Impressão de materiais, 3 – Ambientes demasiadamente grandes frente as turmas alocadas, 4 – Carga horária incompatível com o conteúdo ministrado, 5 – Repetição de itens em diferentes períodos no plano de curso
Espera	1 – Retorno por feedback do professor, 2 – retorno por disponibilidade de vagas, 3 retorno de informações da secretaria, 4 – agendamento com coordenadores e responsáveis.
Transporte excessivo	1 – Movimentação de equipamentos entre laboratórios e salas de aula, 2 – Estoque de materiais nos andares superiores

Processos Inadequados	1 – Processo de compras demasiadamente longo e repetitivo; 2 – Solicitação de cadastros; 3 – Solicitações e protocolos de documentos;
Inventário desnecessário	1 – Excesso de livros; 2 – Excesso de apostilas; 3 – Materiais sem aplicabilidade na área elétrica, 4 – Material na área mecânica sem aplicabilidade; 5 – Materiais na área moveleira desatualizados ou vencidos e 6 – Materiais sem aplicabilidade na área vestuário.
Movimentação desnecessária	1 – Adequação das salas de aula para desenvolvimento de oficinas; 2 – movimentação de alunos entre salas ou laboratórios, 3 – Buscar materiais na biblioteca, coordenação ou outro ambiente.
Produtos Defeituosos	1 – Apostilas defeituosas ou desatualizadas, 2 – livros desatualizados, 3 – materiais com prazo de validade ultrapassado;
Criatividade não utilizada dos funcionários	1 – Alocação de colaboradores em funções desalinhadas com sua formação ou expertises.

Todos os desperdícios identificados foram alvo de estudo, dessa forma, sendo alvo de melhoria. As ações foram coordenadas pelos pesquisadores conjuntamente com os profissionais da unidade educacional.

Comparando o material estimado pelo docente para a realização das aulas práticas, percebeu-se que o consumo era, em média, 18,75% maior que o previsto. Após a realização do controle visual pelos próprios alunos, esse percentual foi reduzido e o material utilizado em aula passou a ser equivalente a 94,12% do estimado, inferior a estimativa. De forma complementar, foi instalado um quadro kanban para controle dos insumos da área metalmecânica. Antes da instalação do Kanban em média, 1 vez a cada mês havia a falta de algum insumo, após a implatação esse número foi zerado.

A organização dos ambientes interferiu no tempo médio necessário para a localização de ferramentas, no primeiro momento, em média eram necessários 44 minutos em um período de 4 horas de aula. Após a instalação dos quadros esse tempo reduziu para 8 minutos em média. Com a realocação de equipamentos e móveis o deslocamento médio dos alunos, que era de 657 metros no período de 4 horas de aula foi reduzido para 49 metros em média.

A identificação dos ambientes educacionais foi realizada por meio da instalação de placas, demarcações no piso, local para depósito de refugos e a instalação de quadros de gestão visual. Ainda nessa etapa, realizado o dia do descarte, a identificação dos equipamentos e os procedimentos de limpeza e desligamento, a demarcação dos corredores, a realocação de móveis e a criação de kits de ferramentas e utensílios por setor. Nos laboratórios de práticas foram instalados quadros para a organização das ferramentas.

Com a instalação dos Tags, a frequência com a qual o ar condicionado ou as luzes dos ambinetes ficam indevidamente ligados foi reduzida em 94%. O tempo médio de organização das salas para o próximo período de aula que era de 16 minutos foi

reduzido para 4 minutos. Esses ganhos foram obtidos em virtude da instalação de POKA YOKE nas mesas dos professores de ambientes como as salas de aula, desenho técnico, robótica e informática.

A solicitação de documentos e demais itens da secretaria passaram a ser registrados em um quadro de recados instalado no ambiente. Um ponto de destaque desse setor foi a redução no tempo de emissão e entreda de certificados reduzindo de 42 dias em média para 5 dias.

Um ganho parelelo e não previsto inicialemnte foi identificado no volume de materiais descartados por desuso, insumos de impressão e tempo disponibilizado para essas atividades. A prática de impressão de materiais didáticos sempre foi realizada pela equipe da biblioteca considerando o número de alunos matriculados nos cursos. Como alternativa, foi proposto a impressão dos materiais frente a solicitação dos docentes, uma prática que poderia ser considerada um Kanban informal. Após a aplicação dessa nova rotina o volume de mateiriais impressos foi reduzido em cerca de 7%.

Em relação a infraestrutura foram realizados ajustes nas torneiras nos banheiros coletivos e a instalação de placas indicativas referente a organização dos ambientes de alimentação. Essas mudanças impactaram diretamente nos custos fixos da unidade gerando uma redução de 31,12% em média no total de energia elétrica consumidos ao longo de um mês.

6 Considerações finais

Objetivou-se com este estudo a verificação da aplicabilidade dos conceitos *Lean* em uma organização escolar de nível técnico, utilizando-se de um estudo de caso. Sendo assim, identificou-se os principais desperdícios por meio da avaliação dos processos, sendo elaborado um projeto de melhoria constituído por seis etapas, reuniões e treinamento, levantamento de informações, identificação de ambientes, organização dos ambientes, instalação de ambientes visuais, análise de desperdícios.

O método apresentado demonstrou ganhos substanciais relacionados ao tempo de uso dos equipamentos e no custo relativo aos cursos, essa condição foi obtida devido ao maior controle e conscientização dos discentes, redução nos gastos com energia elétrica, água e materiais.

Dessa forma, o método pode ser visto como um instrumento simples porém adequado para superar os desafios encontrados na implantação do *Lean* em instituições de ensino técnico inicialmente caracterizada pela resistência ou indiferença da alta gerência.

Entre os principais desafios superados, pode-se destacar a identificação clara em relação aos ganhos obtidos, no estudo de caso, destaca-se os ganhos financeiros por meio da economia de insumos e serviços destinados as atividades educacionais práticas, essas atividades referem-se a atividades realizadas em laboratório como usinagem ou fresagem.

Outro aspecto de destaque é a clareza na descrição das etapas de implantação, apesar de largamente utilizada, a filosofia *Lean,* padece de instrumentos de implantação e

manutenção, em específico, desenvolvidos especificamente para unidades educacionais de ensino técnico.

Sugere-se como continuidade da pesquisa, manter as atividades e ampliar o número de ações e de seus impactos para outros setores da unidade educacional. Um ponto negativo foi a falta de interesse dos gestores regionais frente aos possíveis ganhos a serem obtidos com o projeto. Dessa forma, a falta mobilização e organização de horários, gerou obstáculos que poderiam ser evitados com o apoio da alta gerência.

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Minimizing total implementation cost of a 2-D indoor localization system with a constant accuracy for underground mine tunnels

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Abstract. In this paper, we introduce the problem of minimizing total implementation cost of a 2-D indoor localization system for underground mine tunnels, guaranteeing a constant accuracy. To address this problem, we propose a system based on Cell-ID technique and visible light communication (VLC) technology with square panels of light-emitting diode (LED) lights, which fixes the maximum position error in each cell by considering the distribution of overlapping and non-overlapping cells. Formally, our system is mainly defined by an easy-to-implement algorithm based on a simple order rule. In order to illustrate the usefulness of the proposal, an example is provided. Finally, potential applications in the industrial environments are discussed and future research is proposed.

Keywords: Visible light communication, Indoor localization system, Accuracy, Cost minimization.

1 Introduction

In the last decade, visible light communication (VLC) systems for positioning has gained the attention of researchers due to its merits in terms of accuracy, cost, safety, and reliability for indoor environments [13]. Several works are related to channel design models [10, 8], while others researches assessed signal propagation and interference mitigation [11]. Most of researches related to the physical design of VLC [15, 5, 12] seeks to improve the system accuracy, considering accuracy as a result of the optimized location of the LED lights. Nevertheless, the research carried out by [6] seeks to determine the distribution of circular light-emitting diode (LED) lamps, mounted on the ceiling, in order to provide a 1-D linear positioning system with a constant accuracy along the tunnel. This perspective has large advantages in order to improve safety in mining operations.

Complementary to the previous works in this field, our research integrates the cost and 2-D positioning systems with overlapping and non-overlapping cells,

which allows to explore Cell-ID technique and VLC applications with square panels of LED light in larger mining tunnels.

2 Description of the indoor positioning system

2.1 General overview

We introduce the problem of minimizing total implementation cost of a 2-D indoor localization system with a constant accuracy. Consider underground mine tunnels, where the location is determined into the two coordinate axis (along the tunnel). In this scenario, we assume a 2-D indoor localization system based on Cell-ID technique and VLC technology. A practical implementation of Cell-ID and VLC technology is detailed in [6]. An unique code is assigned to each cell, in order to identify the lamp location. Each LED device is identical and produces a square illumination pattern subject to the used beam angle, which constraints on the minimum and maximum lighting area at the floor level and the position defined by it. Considering that the calculation of the accuracy depends on the amount of error present in the localization [16], several areas could be not necessary covered with a specific and constant error at minimal cost by using the same size of squares LED device.

To face this situation, a solution alternative emerges from the distribution of overlapping and non-overlapping cells. Some similarities with other problems in the family of *packing* are found. Considering the overlapping condition, our problem is close to the *three-dimensional bin packing problem* [9] and the *container loading problem* [3]. However, the most of these problems on 2D do not allow the overlapping elements to be positioned [7]. In addition, these problems consider the number of elements (or boxes) and their dimensions as parameters, no decision variables, with the goal of minimizing the free space [4]. Therefore, the results do not necessarily have to completely cover the surface.

To address our problem, without loss of generality we consider a rectangular area of sides a and b, $a \leq b$.

In the case of non-overlapping cells, a LED device produces a square illumination pattern of side ℓ with a maximum distance error δ between the real and estimated positions. This above value is expressed by $\delta = \frac{\ell\sqrt{2}}{2}$. Then, the projection of nine LED lamps has a coverage area of $(3\ell)^2$. Without loss of generality, we fix the maximum distance error $\delta = \frac{\sqrt{2}}{2}$, with $\ell = 1$. A VLC positioning system projection of nine square LED lamps in a rectangular area with $b = a$ with non-overlapping cells is illustrated in Fig. 1.

To consider the case of overlapping cells, we introduce the concept of *complete cell* as follows:

Definition 1. *A complete cell is a set of equal overlapping cells that defines a maximum distance error $\delta = \frac{\sqrt{2}}{2}$ independent of the number of cell identification codes received.*

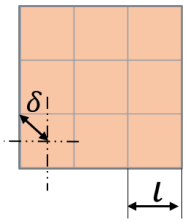

Fig. 1: VLC positioning system projection of nine square LED lamps with non-overlapping cells.

Fig. 2 illustrates a scenario with a complete cell with four overlapping cells of side $\ell = 2$, assuming equal distance between LEDs and identical beam angles. In this case, the mobile node estimated position will depend on the number of identification binary codes received from each cell and the maximum distance error δ between the real and estimated positions still remain the same, as it is depicted in Fig. 1.

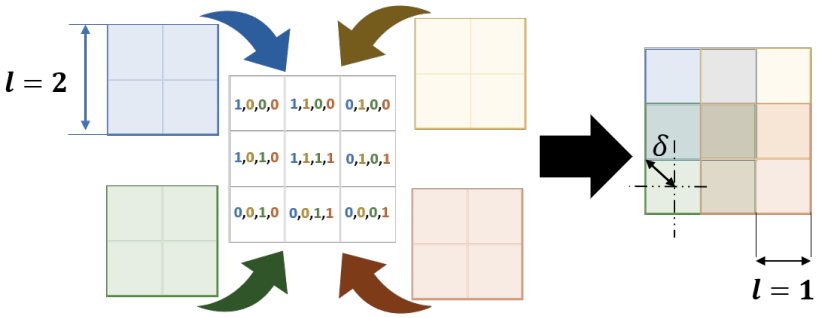

Fig. 2: VLC positioning system with a complete cell defined by four overlapping cells. The binary number with colors represents the possible cell identification codes received.

Theorem 1. *Consider a positive integer number ℓ. A complete cell the side $2 \cdot \ell - 1$, requires a set of ℓ^2 equal overlapping cells of side ℓ.*

The proof is based on geometric Euclidean analysis. The detail is omitted by space constraint.

From these above results, we propose a easy-to-implement algorithm in the next section.

2.2 Algorithm

Let α_ℓ be the cost of a unit cell of side ℓ, $\ell \geq 1$. First, we obtain a feasible solution for the rectangular area $a \cdot b$ by a number $a \cdot b$ of non-overlapping cells of side $\ell = 1$ with a total implementation cost equal to $a \cdot b \cdot c_1$. The previous value represents an upper bound for the objective value of the problem. Second, we compute the complete cell of maximum side $\ell_{\max}$ and the maximum number of each feasible complete cell β_ℓ defined by cells of side $\ell \leq \ell_{\max}$, comparing the implementation cost of a complete cell defined by cells of side ℓ and the non-overlapping cells of side $\ell = 1$ subject to the same coverage area. Finally, the algorithm considers a simple rule defined by the decreasing cost order $(2 \cdot \ell - 1)^2 / \left(\ell^2 \cdot \alpha_\ell\right)$, locating the cells configuration according to it when possible, and completing the remaining area with non-overlapping cells of side $\ell = 1$.

3 An illustrative example

Table 1 shows the parameters considered for an illustrative example, considering a rectangular area.

Table 1: Illustrative example parameters.

Rectangular area	sides	a=10	b=20		
	area	200			

Unit cell side (ℓ)	1	2	3	4	5
Unit cell cost (α_ℓ)	3.00	5.63	8.85	6.13	12.96
Complete cell side $(2 \cdot \ell - 1)$	1	3	5	7	9
Complete cell cost $(\ell^2 \cdot \alpha_\ell)$	3.0	22.5	79.7	98.1	324.0

The initial feasible solution is given by 200 unit cells of side $\ell = 1$ with a total implementation cost equal to 600. Finally, Figure 3 represents the solution obtained by the easy-to-implement algorithm, where the gray squares corresponds to unit cells that define the complete cells. This solution is optimal.

4 Conclusions

This article introduced the problem to minimize the total implementation cost of a 2-D indoor localization system based on Cell-ID technique and VLC technology for underground mine tunnels, guaranteeing a constant accuracy. The system is based on easy-to-implement algorithm based on simple order rule. The usefulness of the proposal is illustrated by an example.

From the obtain results, the benefits of our proposal for transmitting positional information about elements within indoor scenario could be extended

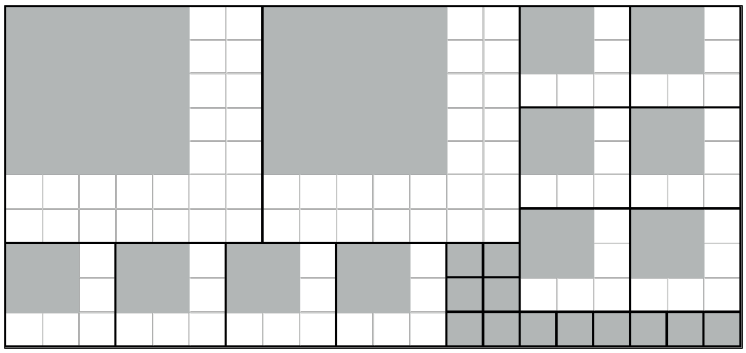

Fig. 3: Optimal VLC positioning system with overlapping and non-overlapping cells for the illustration example. The total implementation cost is equal to 457.3. The number of the considered complete cells defined by the overlapped unit cells of side ℓ equal to 5 and 2; are 2 and 11 respectively. The remaining space is completed with 12 unit cells of side $\ell = 1$.

to the industrial environment, in particular to conceive and design warehouse management systems (WMS), one of the central links in any supply chain [14]. In these systems, the part traceability control is based on detection by RFID systems or manual picking performed by operators with barcode reading devices [1]. However, it can lead to somewhat limited information on the real-time positioning of parts or inventory items. That is, once an item has been removed from its shelf (or rack) and is moved to another location, we only have information about the item being removed, and not about the evolution or path of that item. If there is movement control, it is on the carrier of the element [2]. Thus, our proposal would greatly improve the availability of information, with an easier implementation since it is directly linked to the lighting system.

Finally, future research work could be focused on the formulation of mathematical models and algorithms in order to obtain optimal or approximate solutions for the problem.

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Utilização do método PDCA para melhoria de processos: estudo de caso em um centro de distribuição alimentícia

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Abstract: O presente estudo apresentou a utilização do método PDCA como instrumento de padronização de processos e eliminação de falhas, voltado ao departamento logístico de um centro de distribuição de alimentos do sudoeste do Paraná. No que tange os procedimentos metodológicos, a pesquisa se caracteriza como um estudo de caso aplicado, com abordagem quali-quantitativa, descritiva e exploratória. Os resultados obtidos elucidam que a aplicação da metodologia se mostrou eficiente na identificação dos pontos falhos do processo, e na elaboração de planos de ação com o intuito de mitigar erros no processo de envio de mercadorias aos clientes finais, bem como na diminuição de gastos extras decorrentes de entregas não planejadas e combustível gasto pela frota de veículos. De maneira geral, pode-se observar que, de acordo com as expectativas a empresa alcançou seus objetivos com redução do gasto em combustível com os veículos da frota, melhoria no departamento estudado e desempenho operacional, em cerca de 60%.

Keywords: Método PDCA, Melhoria de Processos, Centro de Distribuição.

1 Introdução

O desempenho de qualquer empreendimento, depende de como é planejada e executada a atividade que se pretende explorar, usando os recursos naturais, materiais e humanos para alcançar os objetivos a que se propõe, considerando a inserção no contexto sócio-econômico e politico [1].

No setor industrial, a constante mudança em busca de aperfeiçoamento e a alta competitividade, fazem com que as empresas se esforcem para a competitividade de classe mundial. Isso também faz com que a manutenção esteja sob pressão crescente, objetivando melhorias, por exemplo, confiabilidade e disponibilidade das instalações de produção, assim como a redução de custos e resíduos. Com a implementação da manutenção centrada na confiabilidade, manutenção produtiva total e manutenção centrada nos negócios, tal conceito evoluiu muito nas últimas décadas [2]. Estes fatores exigem que as indústrias se comportem de maneira diferente adequando-se a esta realidade [3].

Da mesma forma, em um centro de distribuição (CD), os processos devem ser planejados e organizados, a fim de alcançar padronização sem desperdício de tempo. Um centro de distribuição traz como propósito possibilitar maior flexibilidade e dinamismo nas

entregas, no corte de custos de transporte e na armazenagem dos produtos [4]. Os principais objetivos de um centro de distribuicão são: receber, separar, armazenar e expedir os produtos para seus destinos finais.

O estabelecimento de uma rotina, planejamento, controles e melhorias para a manutenção possibilitam alcançar eficiência em termos de disponibilidade dos ativos, com custos competitivos e qualidade elevada [4]. Para tanto, se torna necessário traçar uma estratégia de manutenção adequada para as necessidades específicas da empresa [5].

A prática da melhoria contínua aplicada aos processos possibilita a eliminação da causa do problema em questão, partindo de sua identificação através de mecanismos de controle de processos, isso faz com que a qualidade deixe de ser uma opção e passe a ser vista como sinônimo de sobrevivência, tornando-se assim a satisfação total das expectativas e das necessidades dos clientes, passando a fazer parte da prestação de serviço, assim como do produto, assumindo a melhoria contínua como uma filosofia a ser seguida pelas organizações [6].

Para que a melhoria contínua seja implementada, existem diversas metodologias e suas respectivas ferramentas, capazes de auxiliar em processos de gestão. Uma das metodologias de destaque é o Método PDCA (Plan, Do Check, Action) que é um método capaz de gerenciar tomadas de decisão, com o objetivo de melhorar as atividades de uma organização, sendo também explorado na busca de melhoria de performance, o que torna este método capaz de contribuir significativamente para a obtenção de melhores resultados [7].

Considerando os conceitos apresentados, este estudo objetiva, de modo geral, apresentar a utilização do método PDCA como instrumento de eliminação de falhas em um centro de distribuição de alimentos localizado no sudoeste do Paraná.

Para tanto, foram traçados como objetivos específicos: verificar as causas de problemas operacionais do CD através da análise de processos; aplicar a metodologia PDCA para propor um plano de melhoria.

Este estudo se enquadra, em sua essência, como pesquisa aplicada, pois a finalidade do conhecimento produzido é de aplicação prática, utilizado na solução de demandas reais e específicas.

2 Referencial Teórico

2.1 Gestão da qualidade, gestão de processos e Ciclo PDCA

No meio industrial, tem sido feitos grandes investimentos para promover processos de melhoria contínua e redução sistemática de desperdícios, com a finalidade de se manter elevados índices de competitividade e qualidade dos produtos [1].

Um sistema de gestão da qualidade compreende todos os procedimentos utilizados por uma organização, para gerenciamento de suas atividades [8].

No entanto, na literatura vigente e qualificada, pode-se encontrar versões diferentes para qualidade, sendo a definição de qualidade pautada em atender as exigências do consumidor [9,10].

Os sistemas de gestão da qualidade são um importante meio para a introdução e sistematização da filosofia e dos procedimentos da qualidade nas organizações [11]. Esses modelos de gerenciamento de sistemas são oriundos da crescente complexidade dos processos produtivos, o que possibilita tratar de maneia simplificada problemas de cunho complexo [12].

No entanto, processo é o meio de transformação de inputs em outputs, no chamado processo de agregação de valor [13]. Processo é a produção onde efetivamente ocorre a transição dos inputs em outputs [14].

afirma que os processos devem ser mapeados e inseridos em um fluxograma que discrimina a sequência das atividades a serem realizadas, bem como seu grau de importância, pois na gestão de processos é essencial que cada colaborados tenha consciência do que seu trabalho representa, para que todos os envolvidos no processo possam contribuir para a eficácia do método, assim como deve ser na gestão da qualidade [15].

O Ciclo PDCA, sendo um método de gerenciamento de tomada de decisões, pode garantir o alcance das metas necessárias para a sobrevivência de uma organização [16].

O PDCA é uma ferramenta utilizada para a aplicação das ações de controle dos processos, diretrizes de controle, planejamento da qualidade, manutenção de padrões e alteração da diretriz de controle, com o intuito de realizar melhorias [17]. Dentro do PDCA podemos encontrar outras ferramentas coadjuvantes, como o Diagrama de Pareto, que consiste na apresentação de um gráfico de colunas, que permite a priorização de problemas, entre outras ferramentais. O Diagrama de Ishikawa, ou Diagrama de Causa e Efeito, como é também conhecido, é outra ferramenta da qualidade que fundamenta o PDCA. Sua função é organizar o raciocínio das discussões do problema em questão. O P (plan), D (do), C (check) e A (action), traduzindo do inglês para português significa: plan - planejar; do - fazer; check - verificar; action – agir (olhar Fig.1)

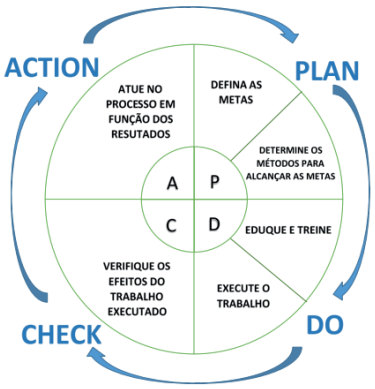

Fig. 1. O Ciclo PDCA

Na primeira fase do ciclo é realizado o estudo prévio de onde há problemas internos na empresa que estão gerando resultados diferentes dos esperados. Uma vez estabelecidos os pontos a serem melhorados, são elaboradas as metas para correção e o que

espera que aquela atividade ou processo desempenhe e alcance. Para esta fase, ferramentas coadjuvantes podem se utilizadas a fim de auxiliar na identificação dos problemas, como por exemplo o Diagrama de Pareto e Diagrama de Ishikawa [15].

O Diagrama de Pareto é representado através de um gráfico de barras verticais que dispõe a informação de forma visual e evidente, o que permite o estabelecimento das metas a serem atingidas [16].

O Diagrama de Ishikawa, por outro lado, possibilita estruturar de maneira hierárquica as causas do problema em questão, além de que foi projetado para ilustrar, de maneira cara, as várias causas que afetam um processo, através de classificação e relação de causas, permitindo estruturar sistemas que necessitem de resposta de forma gráfica e sintética, disponibilizando uma visão detalhada sobre o assunto estudado [18].

A segunda etapa é o "DO", termo originário do inglês que significa: fazer. Nesta etapa será dada ênfase à execução do trabalho onde é importante cumprir os padrões e métodos estabelecidos [3].

A terceira fase trata da verificação das metas e se as falhas foram verdadeiramente eliminadas, para tanto, se os resultados forem positivos, as metas forem atingidas e os objetivos alcançados, o processo pode passar para a quarta fase, no entanto se houver a verificação de que as metas não foram atingidas e as expectativas não foram sanadas, o planejamento precisa ser refeito e as etapas iniciadas novamente.

Na quarta e última fase do ciclo, ocorrerá a tomada de ações corretivas, caso seja necessário ou a padronização do processos adotados, para casos onde os objetivos foram alcançados. Nota-se que esse método é amplamente utilizado pro organizações par gerenciar seus processos internos, de forma a garantir alcance de metas estabelecidas, tendo as informações como fator de direcionamento das decisões [19].

O PDCA padroniza as informações do controle da qualidade, evita erros lógicos nas análises, e torna as informações mais fáceis de serem entendidas. Pode também ser usado para facilitar a transição para o estilo de administração direcionada à melhoria continua [17].

2.2 Cadeia de Suprimentos

A gestão da cadeia de suprimentos é um processo estratégico. Lida com a previsão da demanda, seleção dos fornecedores, fluxo de materiais, contratos, estuda informações e movimentações financeiras, cria novas instalações como fábricas, armazéns, centros de distribuição; se relaciona com clientes, e trata também de questões mais amplas como a economia, a sociedade, o meio ambiente [20].

De maneira geral, a cadeia de suprimentos é uma abordagem sistêmica, a qual demanda alta interação entre os participantes, necessitando de cooperação simultânea de diversos *trade-offs* [21].

Dentre os benefícios do estudo da cadeia de suprimentos de forma integrada destaca-se melhor gestão do fluxo da demanda, a qual pode melhor sinalizar a necessidade de compra e venda de produtos, diminuindo os desperdícios e prejuízos [3].

2.3 Centro de Distribuição

O Centro de Distribuição é uma configuração regional de armazém onde são recebidas cargas consolidadas de diversos fornecedores. Essas cargas são fracionadas a fim de agrupar os produtos em quantidade e sortimento corretos e, então, encaminhadas para os pontos de venda, mais próximos [22].

O CD é um ponto de intermédio entre os fornecedores e o cliente final [23]. Nas empresas sentiram necessidade de utilizar os centros de distribuição, dada a alta demanda de pedidos e a necessidade de melhor gerenciá-los [17,23].

Os centros de distribuição propiciam redução no custo de transporte e, com isso, a maximização dos lucros e da agregação de valor ao produto. Um centro de distribuição que é utilizado por vários fornecedores garante que os mesmos trabalhem com cargas consolidadas. Para consumidores, por outro lado, além da diminuição no custo de transporte, existe a economia de duração de operação gerada, graça ao recebimento de uma única carga, por exemplo, com todos os materiais necessários, ao invés de receber carregamentos divididos e de vários fornecedores [24].

Ao reduzir custos logísticos e aumentar a eficiência na movimentação de mercadorias, o CD acaba contribuindo para a melhora nos níveis de serviço, colocando a empresa tomadora de serviço em um novo patamar de competitividade. Através desse nível de serviço, a empresa pode aumentar sua participação no mercado [3].

3 Metodologia

Para que o conhecimento gerado seja aceito como científico, é necessário que o processo de construção considere regras e procedimentos, além de atentar para o formato, o método e os instrumentos do "conhecer" [25]. A determinação do método científico é relevante para a efetivação do estudo e seus resultados, visto que pretende nortear e delinear os meios utilizados para a sua validação [11].

A pesquisa caracteriza-se como um estudo de caso com abordagem quali-quantitativa, descritiva e exploratória. O estudo de caso é uma pesquisa que busca analisar fenômenos atuais em uma situação real, dentre os maiores benefícios, destaca-se a possibilidade de desenvolver uma nova teoria, e de aumentar o entendimento sobre eventos reais contemporâneos [26]

Ainda, em relação à abordagem do problema, em situações em que há questionamentos subjetivos de indutivos, explana-se como um estudo qualitativo, e nas circunstâncias em que os dados podem ser mensurados considera-se como pesquisa quantitativa [27].

Com o intuito de preservar a identidade da empresa pesquisada, o codinome CDD será adotado para representar a empresa. O processo estudado foi o desenvolvido pelo setor da expedição, com enfoque principal a entrega das mercadorias aos clientes, ou seja, a expedição e a logística. A pesquisa não se retringiu apenas a esse setor, de forma isolada, o setor de faturamento, de maneira específica a Nota Fiscal eletrônica, também presente no processo da expedição foi observado.

Os setores da expedição e faturamento pertencem a departamentos distintos, sendo a expedição parte do departamento de logística e o faturamento parte do departamento financeiro.

O processo do CDD se inicia com o recebimento das cargas consolidadas, sendo as mercadorias conferidas e alocadas de acordo com suas respectivas famílias de produtos; independente da marca do produto, quando recebido pelo CDD é alocado com seus similares (olhar Fig. 2). A organização do local de armazenagem é responsabilidade do setor de expedição.

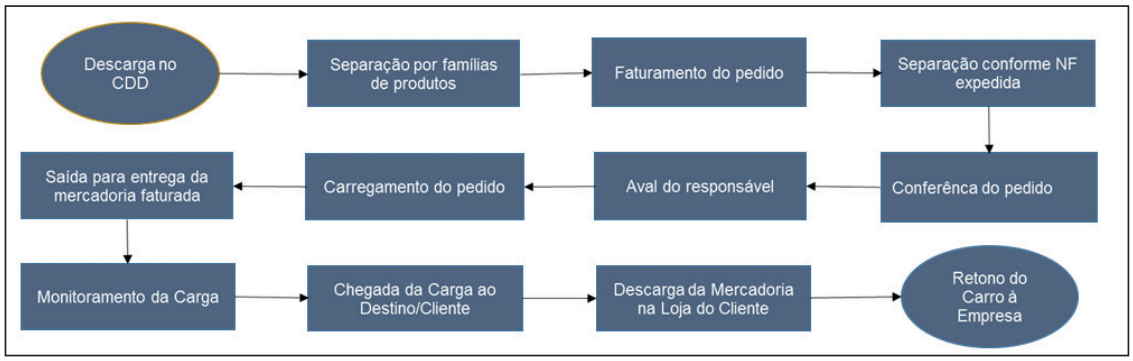

Fig. 2. Descrição do processo de recebimento de cargas consolidadas

Sempre que um cliente efetua um pedido na plataforma on-line, este é recebido pelo setor de faturamento, o qual expede a Nota Fiscal eletrônica (NFe) e a envia ao setor da expedição para que o pedido possa ser separado e, posteriormente, entregue a seu destino final. Esse processo se inicia com a separação da mercadoria constante no pedido, a qual, após separada, é conferida pelo colaborador responsável pelo setor da expedição, o qual assina o pedido, liberando-o para que possa ser alocado no veículo que realizará a entrega.

Como os pedidos dos clientes são entregues em datas específicas, o veículo que realizará a entrega é demandado pelo tamanho e quantidade de pedidos a serem entregues.

Após todos os procedimentos de conferência da carga, a mesma é alocada no veículo de entrega, de modo a minimizar possíveis avarias.

Cada veículo é designado para uma rota específica, estipulada a partir da localização das lojas dos clientes. Todos os veículos que compões a frota responsável pela entrega dos pedidos, carrega um dispositivo GPS, o qual é acompanhado pelo responsável pelo setor da expedição, de dentro da empresa sempre que os veículos saem da empresa para realizar as entregas.

Os dados foram coletados através de observações in loco dos setores estudados e da análise de documentos disponibilizados pela empresa. Após a coleta de dados, as informações coletadas foram tabuladas em questionários eletrônicos e analisadas de

forma qualitativa e quantitativa, pautadas na bibliografia vigente e qualificada. Os resultados obtidos se encontram na seção subsequente deste estudo.

4 Resultados

Esta seção apresenta a aplicação do método PDCA no setor de expedição do CDD, considerando que é o setor que mais gera custos à empresa. A seguinte ordem foi obedecida para a aplicação do método: identificação do problema, observação do problema, análise, planejamento/plano de ação, ação, checagem, padronização e conclusão (olhar Fig. 3). Além da ferramenta PDCA, utilizou-se como ferramenta coadjuvante o Diagrama de Ishikawa e o Diagrama de Pareto.

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Fase	Janeiro	Fevereiro	Março	Abril	Maio	Junho	Julho
Identificação do problema							
Observação *in loco*							
Análise							
Planejamento							
Ação							
Verificação							
Padronização							
Conclusão							

Fig. 3. Cronograma simplificado da aplicação do método PDCA

O estudo ocorreu entre os meses de janeiro e julho, no ano de 2019 e, por meio da observação dos processos desenvolvidos pela empresa, pode-se constatar que haviam alguns gargalos no processo estudado, de maneira específica, na entrega das mercadorias aos clientes. Foi possível identificar a necessidade de realizar melhorias entre a comunicação dos setores envolvidos, considerando que havia demora excessiva entre o faturamento do pedido e a expedição da NFe, acarretando no atraso de alguns veículos, bem como entregas não programadas, desenvolvidas em regime de urgência, dada a necessidade de um cliente por determinada mercadoria, gerando custos extras com frota de veículos de entrega, para tanto, foi realizado um Braisntorming com os responsáveis pelos setores estudados, juntamente com a equipe gestora da empresa, (olhar Fig. 4), para que as possíveis causas de problemas pudessem ser levantadas e , posteriormente, corrigidas.

8

Causas	Possíveis Soluções
Entregas Imediatas	Reorganizar faturamento dos pedidos. Entregas a cada 14 dias
Movimentação desnecessária dos carros e colaboradores	Efetuar entregas somente quando necessário/Cada colaborador deve desempenhar uma função e ser responsável por ela
Excesso de manutenção corretiva nos carros/perda de tempo com conserto que origina gastos com outro carro para efetuar a entrega do pedido	Políticas de incentivo e pré agendamento para as manutenções preventivas.
Carros da frota que apresentam problemas	Propor a checagem e cuidados com os carros
Falta de organização na hora de carregar a mercadoria nos carros	Delegar a função a um colaborador que deverá conferir a mercadoria e organizar o carregamento das mercadorias dentro dos carros, sendo responsável pelo processo.
Falta de comunicação entre os setores, em específico, a direção e o setor logístico	Abrir espaço nas reuniões para sugestões e reclamações, levando em conta as ideias dos colaboradores.

Fig. 4. Causas latentes de problemas no CDD

Após levantamento, medidas iniciais estudo de ações corretivas e planejamento foram analisadas, para que se pudesse aplicar o método PDCA. O Diagrama de Pareto (olhar Fig. 5) foi aplicado como ferramenta coadjuvante de identificação.



Fig. 5. Diagrama de Pareto relacionado aos problemas do CDD

Com a elaboração do Diagrama de Causa e Efeito, o departamento logístico pode compreender de forma mais os possíveis erros identificados, podendo agir de maneira a adequar seus processos e reorganizar suas entregas.

As respostas para as sete perguntas foram obtidas juntamente com a diretoria da empresa, pautadas em estudos analíticos e sugestões dos colaboradores visto a necessidade de respaldo para cada ação que seja tomada dentro da empresa.

Após a implementação da ferramenta da qualidade PDCA, a equipe do setor logístico, como um todo, passou a enxergar o processo por eles desenvolvido de uma maneira mais crítica e técnica. Os colaboradores desse setor passaram a ter mais disciplina e cuidado ao desempenhar qualquer atividade envolvendo a logística e a organização do depósito, a partir disso pode-se notar que os resultados obtidos com a implementação de todos os passos do PDCA foram positivas do ponto de vista financeiro e das relações entre os setores da empresa, pois as mudanças proporcionaram organização e melhor sintonia entre os setores, departamento e os colaboradores da empresa.

O PDCA continua sendo aplicado, principalmente onde ainda existem falhas, não somente no setor da logística, mas na empresa como um todo, ou seja, o ciclo é reiniciado passando por todas as etapas citadas; o PDCA "gira", assim garantindo a melhoria contínua.

Em um comparativo entre o mesmo período dos anos de 2018 (olhar Fig. 6), onde a melhoria ainda não havia sido aplicada, e de 2019, já com a implementação da melhoria, pode-se observar valore significativos relacionados a adequação das falhas identificadas.

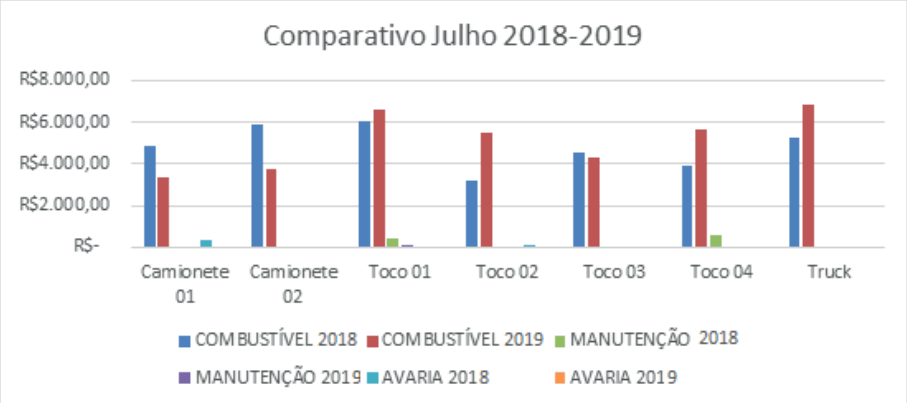

Fig. 6. Comparativo das despesas com a frota, entre o mesmo período dos anos 2018 e 2019.

O gráfico acima foi estruturado com valores obtidos através do levantamento e controle de custos, cujo o departamento da logística é responsável. Tais valores correspondem ao gasto mensal (mês de julho), dos anos de 2018 e 2019, bem como as incidências dessas causas também contadas mensalmente.

Ao observar o gráfico, pode-se notar que os custos com combustível e manutenção dos carros, no mesmo período dos anos de 2018 e 2019, diminuíram significativamente, visto que as entregas passaram a acontecer apenas a cada quatorze dias, dada à necessidade de mudança no plano de entregas.

O foco do estudo teve como base as entregas feitas logo após o faturamento das mercadorias, ou seja, assim que um pedido é faturado, o caminhão sai para entregar.
Em média, um caminhão roda 3,45 Km com um litro de óleo diesel, então, para uma cidade cuja distância é de aproximadamente 280 Km, partindo da sede da empresa, considerando a ida e a volta e admitindo que o valor de um litro de óleo diesel seja em torno de R$ 2,88, o gasto com combustível seria de aproximadamente R$ 467,00.

A descarga nessa cidade, por exemplo, antes da implementação da melhoria e reformulação do plano logístico, era feita sempre após o faturamento do pedido do cliente, o que girava em torno de cinco vezes por mês, então, o gasto de combustível, somente com essa cidade, seria de aproximadamente R$ 2335,00 mensais.

A partir da efetivação das melhorias, o caminhão passou a descarregar apenas duas vezes por mês nessa rota, totalizando um gasto de R$ 934,00, que comparado ao valor anterior, significa uma redução de aproximadamente 60 % do valor gasto apenas com combustível.

Ao final de doze meses, para um único caminhão, o valor poupado será de R$ 16.800, 00, aproximadamente, em combustível, salvos eventuais contratempos como quebra do caminhão ou possíveis acidentes.

5 Considerações finais

Com a aplicação do método PDCA, foi possível sugerir um plano de ação, bem como ações corretivas, quando necessário, com o objetivo de mitigar erros ou torná-los inexistentes. De acordo com a perspectiva e projeção, a empresa conseguiu alcançar seus objetivos, com melhoria no nível de serviço e desempenho operacional de, aproximadamente, 60%. A metodologia utilizada foi eficaz, demonstrando ser uma medida viável e que pode alcançar resultados esperados e, de certa forma, essenciais à empresa.

Como toda empresa, negócio ou ramo de atividade, a empresa pesquisada apresentava a necessidade de aperfeiçoamento, o qual foi planejado e demonstrado a partir de mudanças feitas por um grupo de pessoas que receberam instruções e aperfeiçoamento quanto à técnica de melhoria empregada.

No caso da empresa em questão, onde sua essência é a logística, os resultados tardaram a aparecer pois a mudança não ocorreu de forma imediata, porém, através de comparações entre as planilhas de entrega, que constavam as quilometragens dos carros, de antes e depois da implementação da melhoria, pode-se observar um melhor aproveitamento do tempo de trabalho disponível, o qual antes, os motoristas passavam apenas na estrada e agora podem usar o tempo em que não estão fazendo entregas para

organizar e limpar o CDD, bem como para fazer a manutenção preventiva e limpeza nos carros.

Através de relatórios semanais elaborados pelos colaboradores responsáveis pelos departamento de logística e faturamento, pode-se observar diminuição nos custos com manutenção corretiva e com avaria de carga e, consideravelmente, a redução com custos de combustível e pedágios, por exemplo, um caminhão toco que antes das melhorias custava cerca de R$ 7000,00 mensais à empresa, após a efetivação das melhorias passa a custar em média R$ 3500,00. Nesse caso houve redução de 50% do valor gasto inicialmente.

Os resultados obtidos, apesar do curto período de tempo, são satisfatórios, pois as mudanças proporcionaram uma melhor organização nos processos desenvolvidos pela empresa, principalmente nos que apresentavam mais falhas, como era o caso do plano logístico.

Juntamente com as melhorias no plano logístico da empresa e treinamentos de pessoal, o que tem papel fundamental para o constante aperfeiçoamento da empresa são as pesquisas de satisfação aplicadas aos associados por meio de e-mails, onde o cliente tem liberdade para opinar sobre o serviço que é oferecido pela empresa, bem como reclamar de algo ou sugerir alguma mudança. Tudo isso é levado em consideração dentro das reuniões mensais da presidência e diretoria e, o que for pertinente, é repassado aos envolvidos de cada setor.

As melhorias foram recentemente implementadas, porém, até o final do segundo semestre de 2019, a empresa espera obter resultados ainda melhores com os valores poupados que poderão ser redirecionados para o aumento da frota e expansão da empresa.

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Utilization of the Rice Husk (Oryza Sativa) for the Elaboration of an Agglomerated Material for the Construction of Housing in Cucuta, Norte De Santander – Colombia.

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Abstract. To maximize the use of waste from rice production and the strengthening of the ceramic industry sector in Norte de Santander, the use of rice husk (Oryza sativa) generated as a by-product of waste in the rice industry was evaluated, as raw material for the production of a material agglomerated with clay (brick), for the housing construction sector. According to Suryana (2018) [8], the silica-rich composition of the rice husk is an advantage in the manufacture of ceramics; Portillo (2013) [10] evaluated the use of rice husk in its natural state, ground or ash for the manufacture of elements intended for construction; Díaz (2013) [11], found that composite materials for masonry use clay or cement as a matrix and as reinforcement, agricultural residues such as rice husk due to its low density, resistance to stress and low thermal conductivity. The rice husk process was carried out by 3 stages: the characterization of raw materials, (rice husk and clay); the realization of two formulations varying the amounts of rice husk and clay, (10% husk 90% clay) and (20% husk 80% clay); and the quantitative evaluation of the properties of the agglomerated material. The formulation of 10% rice husk and 90% clay, complied with the Colombian Technical Standard 4205, which establishes the mechanical strength parameters for the compression of vertical drilling masonry units such as blocks and bricks which makes it optimal for housing construction.

Keywords: 1.Husk 2.Clay 3. Agglomerated 4.Rice 5. Construction

1 Introduction

According to the Development Plan for Norte de Santander, Colombia 2016-2019, "Un Norte Productivo para todos", the rice chain represents an important economic line of the department according to the Governorate of Norte de Santander (2016) [1]; however, according to Sierra (2009) [2]; 20% of rice production is a by-product called husk, which due to its physical-chemical constitution, is a waste of very difficult biodegradation, its use is limited and it represents a considerable problem when it is incinerated in the open, generating a negative impact on the environment.

According to Sierra (2009) [2], in Colombia, although the use of rice husk is limited, different alternatives for the use of this raw material have been studied; at an international level, the characteristics of rice husk related to combustion have been studied, according to Wang (2018) [3], by increasing the proportion of rice husk, both the combustion temperature and the amount of nitrogen oxides decrease and the effect is gradually reduced. Rice husk has also been used in the construction sector, according to Ferrão (2017) [4], rice husk has been proposed as a substitute for traditional asphalt pavement fillings; In a study conducted by Widiarini (2018) [9] the porosity of a material composed of silica from rice husks was analyzed

On the other hand, the quality of the clays of the Department of Norte de Santander for the elaboration of materials destined to the construction, have also been evaluated, Rozo (2013) [12], determined the physical and mechanical properties of H10 blocks manufactured in the metropolitan area of Cúcuta.

To maximize the use of waste from rice production, the strengthening of the ceramics industry sector in Norte de Santander and thinking about the need that the construction sector has for constant innovation through environmentally friendly projects, the use of rice husk (Oryza sativa) generated as a by-product of waste in the rice industry was evaluated, as raw material for the elaboration of a material agglomerated with clay, intended for the housing construction sector; this process was carried out through 3 stages: the first consisted in the characterization of the raw materials, (rice husk and clay); the second stage consisted in the realization of two formulations varying the amounts of rice husk and clay, (10% husk 90% clay) and (20% husk 80% clay), however, it was only possible to work with the first formulation and the third stage consisted in the quantitative evaluation of the properties of the agglomerated material, the methodology used to determine the physical and mechanical properties of bricks of agglomerated material was taken from Colombian Technical Standard NTC 4017 [5], methods for sampling and testing of masonry units and other clay products; the analysis that was made to each of the samples was the determination of the mechanical resistance to compression.

2. Materials and methods

2.1. Characterization of rice husk and clay. To characterize the rice husk, the humidity percentage tests were carried out, chemical analysis of ashes, lignin and cellulose; for carrying out these tests, the particle size of the rice husk was not reduced.

To perform the characterization of the clay, an extruded ceramic physical analysis was used, in which parameters such as: dry conditions (length and mass), firing conditions (length and mass), dry shrinkage, shrinkage in cooked, dry mass losses, cooked mass losses, percentage of water absorption, percentage of initial moisture and retained on sieve 230; 10 clay samples were used to carry out this analysis.

The tests that were applied to characterize the clay are governed by the Colombian Technical Standard (NTC 4017) [5] , which establishes the methods for sampling and testing of masonry units and other clay products which allowed to identify the chemical, physical and ceramic characteristics of clay.

For the physical-ceramic characterization, the extrusion shaping method was used, the mixing water was calculated based on the plasticity of the sample, a rectangular nozzle was used and 10 cm long test tubes were made. The analysis of content retained on a sieve was carried out taking into account the procedure established in the ASTM C325 standard. Likewise, linear shrinkage in drying and cooking was measured; the drying shrinkage was made with specimens of known dimensions, which were subjected to drying at 105 ° C for 24 hours, and the firing shrinkage was carried out with the initial dimensions of the dry specimens and the final dimensions of the fired specimens.

The calculation of the contraction was made by measuring the difference in dimensions and thus determining the percentage of contraction of the specimens, and with the data of the difference in dry mass and in firing, the losses due to calcination were determined. Water absorption was determined following the methodology set forth in the NTC 4321-3 standard [10].

2.2. Design of the formulations. Two formulations were designed varying the amounts of rice husk and clay, (10% rice husk and 90% clay) and (20% rice husk and 80% clay), the first formulation allowed the extruded process, of which five samples were made, which were prepared according to the Colombian Technical Standard NTC 4017 [5].

2.3. Quantitative evaluation of the properties of the agglomerated material. The methodology used to determine the physical and mechanical properties of bricks of agglomerated material, is based on the Colombian Technical Standard NTC 4205 [6], the quality of the requirements that must be met by cooked clay bricks. The analysis performed on the five specimens was the determination of the mechanical resistance to compression.

The technique used to determine the physical and mechanical properties of agglomerated material bricks was taken from NTC 4017, methods for sampling and testing of masonry units and other clay products, where the procedures for selection and preparation of the sample. The analysis that was carried out on each of the ten bricks (five for each formulation), was the determination of the mechanical resistance to compression.

According to Rozo (2013) [12], the resistance to compression of clay brick, f'cu, is used as a quality control in the elaboration (dosage of the materials, temperature and time per burning), to know the quality of the materials and the raw material used in the manufacture of brick and to find the compressive strength of the masonry, f´m, from formulas that relate the properties of the unit and the mortars. The dimensions of each

of the bricks (length and width) and the weight were taken. The results were compared with the data established in the NTC 4205[6], standard which sets the requirements that ceramic bricks and blocks must meet, used as masonry units and establishes the parameters with which the different types of stone are determined.

3. Results and discussion

3.1. Results of the physical chemical characterization of rice husk. The results obtained from the analysis on dry basis of the rice husk used as sample for the elaboration of the agglomerated material, are observed in table 1.

Table 1. Results of the physico-chemical analysis of rice husk

Essay name	Result	Method
Ash	16.99%	AOAC 942.05
Acid Detergent Fiber (FDA)	52.46%	AOAC 973.18
Humidity	7.56%	AOAC 925.10

(Test result, 2018)

The results of the ash test are detailed in table 2 and compared with those obtained by Baller (2016) [7].

Table 2. Result of percentage of ash of rice husk present in 2 investigations

Sample	Analysis # 1 Baller (2016)	Analysis # 2 Authors (2018)
M1	17.32	16.91
M2	15.61	16.89
M3	17.07	16.92
Average	16.75	16.99

Fuente: (Justein Baller ., Alejandro Ríos, 2016)

Unlike the study by Baller (2016) [7] in which the determination of the percentage of ash is made in a time of 2.5 hours obtaining an average of 16.75% of ash, in the present investigation, 5 were required hours, obtaining a 16.99% ash.

Once the FDA test was done and comparing the results with the Baller (2016) [7] it is evident that the FDA percentage obtained was 52.46%, result lower than that obtained by Baller (2016) [7] in which a 64.39% FDA was obtained. It is evident that the fibrous amount of the plant tissue corresponding to cellulose and lignin is lower.

Comparing the percentage of humidity obtained with 7.56%, with the results of the study carried out by Baller (2016) [7] 8 to 15%, it is observed that the rice husk used in

this research has a lower amount of water, which favors the elaboration of the agglomerated material.

3.2. Results of the physical-chemical characterization of the clay:

To know the state and the physical and chemical composition of the clay used in this investigation, two tests were carried out, one physical (physico-ceramic) and one chemical (x-ray fluorescence), through which it was possible to observe the conditions that the clay has tomake the agglomerated material and check its mechanical resistance to compression.

3.2.1 X-ray fluorescence results

The X-ray fluorescence results were provided by the Sigma brickyard, where the following chemical composition of the clays is established: high contents of silicon 64.3%, aluminum 19.3%, iron 5.48%. And when comparing it with the analysis carried out by Cáceres, Sánchez & Chaparro., (2017) I was verified that the region has a high quality of clays since both studies reflect a high content of these elements, 5.48% of Aluminum represents the characteristic color of clay used in this research higher than the 4.73% present in the previous author's test. The 64.3% of silicon content is higher than the 28.96% obtained by Cáceres et al., (2017) which shows that the clays of our region have faster cooking speed. Likewise, the difference in the proportion of other elements found in the sample used for this research, but at the same time, as in the research of Cáceres et al., (2017) they present a low content of organic material, which is favorable, since the lower amount of organic matter avoids that in the cooking process there are empty spaces due to the consumption of this material [13].

3.2.2 Results of the ceramic physical characterization of clay. Table 3 shows the results obtained when performing the physical extruded ceramic analysis, to the formulation of 10% rice husk and 90% clay.

Table 3. Physical analysis by extruded ceramic

Sample.	Temp °C	Dry Condition		Cooked Condition		Contraction		Lost of mass		Water Absorption (%)
		Length (mm)	Mass	Length (mm)	Mass	Dry (%)	Cooked (%)	Dry (%)	Cooked (%)	
1		90.00	88.51	83.89	58.97					
2		90.00	85.88	84.39	57.16					
3		90.00	87.30	84.14	58.04					
4		90.00	85.72	84.45	57.12					
5	980	90.00	86.15	84.41	57.19	3.01	3.53	23.19	13.41	23.12

(Test result, 2018)

At the beginning of this extrusion process, the homogeneous mass consisting of rice husk and clay in the proportions mentioned above, an initial humidity of 1.05% was presented and an extruded pressure of 35 mmHg. There was a low level of material change in length with a contraction of 3.01% in dry material. On the other hand, these results show a contraction of 3.53% and a mass loss of 13.41%.

3.3. Results of the design of the formulations. From the characterized raw materials, two formulations were made, one with 10% rice husk and 90% clay and another with 20% rice husk and 80% clay; the elaboration of agglomerated material, was carried out according to the Colombian Technical Norm NTC 4017 [5], through the processes of mixing, forming, drying and firing of the samples, Figure 1, shows the process: mixed, extruded, drying, and cooking.



A B C D

Fig 1. A. Mixed, B. Extruded, C. Drying, D. Cooking

3.4. Result of the quantitative evaluation of the properties of the agglomerated material. The test of mechanical resistance to compression, was carried out in the treatment of 10% rice husk and 90% clay, an average breaking load of 205.79 N. was applied to each muestra. The ten test pieces evaluated from the formulation to 10% of rice husk had rectangular shape and average dimensions of 113.64 millimeters long and 36.60 millimeters wide.

It was found that the samples comply with the compressive mecanic strength properties of vertical drilling masonry units such as blocks and bricks, established in the Colombian Technical Standard NTC 4205 [6], whose parameters are between 100 kgf/cm2 to 140kgf/cm2.

4. Conclusions

The Colombian technical standard (NTC 4205) used for testing masonry units and other clays and to evaluate the chemical, physical, and ceramic characteristics of the clay establish a mechanical resistance range of 100 kgf / cm2 - 140 kgf / cm2, the agglomerated material produced in this research has a mechanical resistance of 99.5 kgf /

cm2, which reflects that the percentage of rice husk used to make a more resistant solid brick must be less than 10%.

The absorption of water that the Colombian Technical Standard 4205 stable must be in a range of 17 - 20%, once the material has been carried out in this investigation has an absorption higher than the established range, yielding a percentage of 23.12%. What would facilitate the risk of mold appearance in the long term, this characteristic is presented by the amount of rice husk used in the manufacture of the agglomerated material, since when the material is baked, pores are generated due to the presence of rice husk, which facilitates the entry of moisture to the solid brick.

From the physical analysis by extruded ceramic it was found that the material in its drying process after cooking obtained small loss of length, went from 90mm to 83.56 mm, which shows that the mixture of 10% rice husk and 90% clay is suitable for making this type of agglomerated material.

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GESTION DE INVENTARIOS PARA UNA PYME

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RESUMEN

Las empresas cuentan con distintos tipos de procesos en su cadena logística. De esta manera, el valor añadido que se entrega a cada eslabón genera un arma competitiva fundamental, tales como excelencia y diferenciación en el servicio de entrega, acoplarse a la tecnología y adelantarse a lo que necesitan o esperan los clientes, lo que trae como consecuencia que las empresas deben tener una eficiente gestión de inventario y recursos. Por lo que en este trabajo se estudia el caso de una Pyme, empresas que necesitan gestión de inventario para no perder clientes. En este caso se modela y simula el proceso de inventario y ventas utilizando Bizagi Modeler, con lo cual se lograron obtener los quiebres. Se modeló y simuló la situación actual y propuesta dando como resultado en la situación propuesta a un valor entre 0 y 0,5%

Keywords: Gestión de Inventarios, Simulación, BPM

1. Introducción

Las empresas necesitan aprovisionarse de bienes y servicios para el desarrollo de sus actividades. Estos aprovisionamientos se acumulan en las empresas y deben ser gestionados para su correcta manipulación y conservación. Las pequeñas empresas deben contar con las competencias y habilidades suficientes para mejorar en forma permanente la gestión de sus recursos y así permanecer insertos en el mercado.

Para que las empresas tengan un impacto positivo en la satisfacción del cliente, es importante contar con una adecuada gestión de inventario para hacer frente a la demanda que se presente, evitando quiebres de stock que dificulten el proceso de ventas. Además de brindar una excelente atención al cliente diferenciándose de la competencia desde que se llega a la tienda hasta un servicio post venta.

Actualmente por efecto de la pandemia la empresa en estudio, empezó a trabajar online, comercio electrónico, por lo que cada vez la gestión de inventario sea hace necesaria para un mejoramiento de atención a los clientes, dado que en varios casos, los clientes, cuando no existe un producto este se pierde, si los clientes deben esperar el producto, estos esperan y vuelven el día que esta el producto en tienda.
Por las razones anteriores, el objetivo de este trabajo es proponer mejoras a la gestión de inventario, con la herramienta de simulación de Business Process Management (BPM), Bizagi Modeler para una pequeña empresa (Pyme) de Joyería, la cual se especializa en comercializar artículos de lujo como, joyas de oro de 18k y 24k tanto en tienda física como online. Se destaca que según el Ministerio de Economía las Pymes en Chile son un 48,7% de las empresas.

2. Revisión Bibliográfica

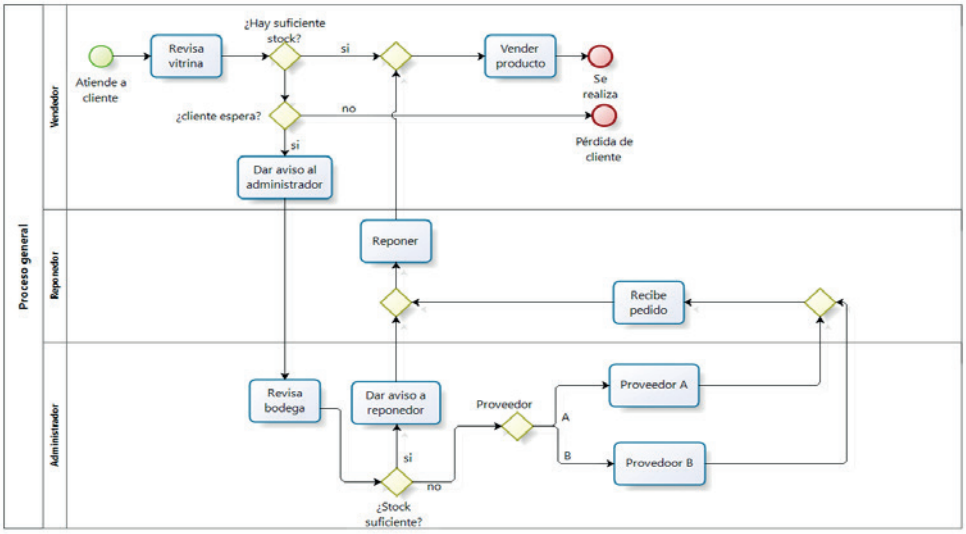
Según Christopher (1994), Prida y Gutiérrez (1996), Gómez y Acevedo (2000) el valor añadido que incorpora la logística en cada uno de las partes del sistema logístico constituye un arma competitiva importante. Tal es el caso de la excelencia en el servicio de entrega, el liderazgo en la diferenciación del producto, la gestión con un mínimo de costo o el servicio logístico al cliente sobre la base de una eficiente gestión de los inventarios.
Según Putra, Santoso (2020), las PYMES identifican las esferas contextuales que pueden orientarlas para utilizar con éxito el comercio electrónico y hacer realidad sus posibles beneficios. Por otra parte se dice que el comercio electrónico tiene un impacto positivo en el rendimiento y el impacto a nivel estratégico es indirecto, mediando a través de los niveles operacionales y de gestión.
En Nemtajela, Mbohwab (2017) la gestión de inventario debe recibir la atención que merece para que la empresa siga siendo competitiva, flexible para la demanda y a bajo costo. Los inventarios son difíciles de gestionar y controlar, y a los administradores de inventarios les resulta difícil saber cuándo pedir y cuánto pedir.
En Silva (2018), también se utiliza , la metodología BPM que le permitió simular los tiempos y el costo de cada uno de los procesos de gestión de inventarios, de una empresa Pyme en Guayaquil , Ecuador, lo que le permitió documentar todos los procesos del centro de distribución de la empresa logrando la optimización de sus recursos.
Por otra parte Morocho 2019 dice que los flujogramas se han utilizado a nivel mundial como una herramienta gráfica para describir la secuencia de actividades que corresponden a los procesos, además traen beneficios como

minimización de errores, relacionados con los protocolos de ejecución de actividades en las empresas. Además modelan los procesos para mejorar la gestión de inventarios con Bizagi Modeler.

3. Metodología

Primeramente se recopilan los datos de las ventas históricas de la empresa, y se clasifican con la metodología ABC para ordenar los artículos según los que más generan ingresos, para agrupar y trabajar de mejor manera los datos.
Una vez obtenidos los productos que generan mayores ingresos, los cuales son: tipos de aros 1, y 2 , collares, y pulseras, todo los artículos de oro de 18kilates.
El proceso de venta e inventario se diseña en Bizagi Modeler donde se obtienen los quiebres, para mejorarlos.
El diseño del proceso actual se muestra en **Figura 1.**

Figura 1: Proceso de ventas y stock



En la Figura 1, se visualiza que el proceso cuenta con tres participantes vendedor, reponedor y administrador. Cada uno de estos actores tiene actividades específicas a desempeñar. El proceso empieza cuando el vendedor atiende a un cliente y finaliza cuando el cliente compra un producto disponible o se retira por falta de stock.

El proceso cuenta con un quiebre, como se muestra en el diseño, cuando el cliente no quiere esperar porque no existe stock del artículo que desea, por lo que se pierde el cliente.
Una vez diseñado el proceso, se simula con Bizagi Modeler, para obtener los resultados de la situación actual, y la situación propuesta.

4. Proceso de simulación

Para realizar el proceso de simulación, se supone que la entrada de clientes se distribuye según una distribución Normal, con una media de 12 min., es decir cada 12 min. entra un cliente, esto con una desviación standar de 2, el proceso se simula para un mes, con un horario de 8 hrs. los 7 días de la semana. Otro supuesto es que los clientes pueden solicitar comprar más de un artículo a la vez, y hasta 100 artículos a la vez, los datos obtenidos son de la situación actual.

El proceso de la situación actual, con datos históricos parte solicitando stock para un mes, donde el lead time es de 1 semana y se solicitan pedidos de 400 productos, en el mes.

La simulación se llevó a cabo solo a los productos que dejan mayor margen, como se explicó en el capítulo 3 que son anillos de dos modelos distintos, pulseras de, cadenas, todos los productos el oro solo es de 18 kilates.

5. Resultados de la simulación.

Para simular el proceso actual, se realizaron alrededor de 10 simulaciones, hasta llegar a la mejor solución que es:

- para aros tipo 1 se tiene que solicitando 400 pedidos al proveedor al mes, el 89% de los productos solicitados son atendidos, en cambio un 11% no son atendidos por lo que se pierden los clientes.
- para aros tipo 2 se solita 100 pares al proveedor al mes, el 89% de los productos solicitados son atendidos, en cambio un 11% no son atendidos por lo que se pierden los clientes.
- para pulseras se solicitan 720 pulseras al proveedor al mes, el 82% de los productos solicitados son atendidos, en cambio un 18% no son atendidos por lo que se pierden los clientes.
- Para cadenas se solicitan 260 unidades al proveedor al mes, el 82% de los productos solicitados son atendidos en cambio un 18% no son atendidos por lo que se pierden los clientes.
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Para la situación propuesta, donde se realizan varias simulaciones para obtener el mínimo de productos solicitados no atendidos se tiene;

- para aros tipo 1 se tiene que solicitando 2000 pedidos al proveedor al mes, el 99,5% de los productos solicitados son atendidos en cambio, un 0,05% no son atendidos por lo que casi no se pierden los clientes.
- para aros tipo 2 se solita 1000 pares al proveedor al mes, el 99,5% de los productos solicitados son atendidos en cambio un 0,05% no son atendidos por lo que casi no se pierden clientes.
- para pulseras se solicitan 2400 pulseras al proveedor al mes el 100% de los productos solicitados son atendidos en cambio un 0% no son atendidos por lo que no se pierden los clientes.
- Para cadenas se solicitan 1100 unidades al proveedor al mes, el 100% de los productos solicitados son atendidos en cambio un 0% no son atendidos por lo que no se pierden los clientes.

Se tiene que al aumentar el stock al mes, con lo cual se disminuye prácticamente a 0 los clientes que se pierden,

6. Conclusiones

En el presente trabajo se ha presentado un problema real de gestión de inventario en una Pyme. Para la cual se utiliza el Bizagi Modeler, logrando resultados deseados.

Por otra parte le el modelo propuesto ayudara a la empresa, a mantener un stock mensual de manera de no perder clientes, con lo que se produce un aumentos en las ventas, y así la disminución de pérdidas de clientes.

Como conclusión se tiene que en la situación propuesta es posible disminuir al mínimo a los clientes insatisfechos de un 11% a un 0,5 % para los aros tipo 1 y2, y de un 18% a un 0% para pulseras y collares, en estos dos últimos casos no se pierden clientes.

Se espera en el futuro simular otros procesos de la empresa, así como también para otros artículos y evaluar económicamente el proceso.

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Current Issues in Flexible Manufacturing using Multicriteria Decision Analysis and Ontology Based Interoperability in an Advanced Manufacturing Environment

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Abstract. The manufacturing industry is undergoing a major transformation based on the emerging industry 4.0 technologies, such as cloud computing, big data, internet of things and cyber-physical systems. These novelty technologies aim at providing central management for the user's flexible manufacturing requirements and information. Also, the advent of these technologies has transformed the process planning and became crucial for the building of knowledge-based process planning environments. However, current praxis cannot deal with all semantic issues within this new paradigm, as requirements must be clear, consistent, measurable, stand-alone, testable, unambiguous, unique and verifiable. In this context, multicriteria decision analysis models have gained focus of the scientific and industrial communities as a support tool for the decision-making process in the product development and advanced manufacturing as these processes excel in environments with numerous and conflicting alternatives, providing the optimal alternative. Therefore, the main objective of this research is to highlight the current issues and research tendencies regarding ontology-based interoperability systems, multicriteria decision analysis and their integration. To achieve this goal, it will be applied a literature review on the targeted technologies, discussing the current tendencies of the field and the main issues regarding their implementation and integration. Finally, the paper points themes for further research and indicates viable concepts that can compose a solution for the gaps in a systematic manner.

Keywords: Advanced Manufacturing Systems, Semantic Interoperability, Multicriteria Decision Analysis, Flexible Manufacturing Systems Process Reconfiguration.

1 Introduction

The manufacturing industry is undergoing a major transformation based on the emerging industry 4.0 technologies, such as cloud computing, big data, internet of things and cyber-physical systems. These novelty technologies aim at providing central management for the user's manufacturing requirements and information. Also, the advent of these technologies has transformed the process planning and became crucial for the building of knowledge-based process planning environments.

Furthermore, over the last two decades, the manufacturing industry has compacted their product lifecycles through the capture and integration of lifecycle knowledge in product development. This resulted in an almost simultaneous processes, which provided efficiency and flexibility while also increasing the product's final quality [1]. This is accentuated by the interconnection of the product development with trends on integrated manufacturing systems, smart factories, and concept and technologies of Industry 4.0 [2] However, current praxis cannot deal with all semantic issues within this new paradigm, as requirements must be clear, consistent, measurable, stand-alone, testable, unambiguous, unique and verifiable [2] [3].

Flexible manufacturing systems are considered the future of manufacturing because of their adaptable nature. In these systems basic modules, such as, the working machines, the material handling system or the manufacturing control system can be rearranged, interchanged or modified adapting the production system according to the enterprise's requirements. In this context, the performance of these systems is related to the system's capability and the planning and scheduling data in agreement with the market demands. Yet, as the market demands change in time the system's capabilities need to adapt to these changes. Thus, these changes can cause problems such as increase in the production time, cost and can decrease the final product's quality.
As the product's design and its manufacturing capabilities are closely related, the manufacturing system is desired to be reconfigurable in order to easily adjust for design changes that can occur in the product.

Currently, multicriteria decision analysis models have gained focus of the scientific and industrial communities as a support tool for the decision-making process in the product development and manufacturing as these processes excel in environments with numerous and conflicting alternatives, providing the optimal alternative. In this context, the multicriteria decision analysis makes for more consistent decision making as subjectivity and possible trade-offs can be contextualized and incorporated into these models. With these characteristics the multicriteria decision analysis can be incorporated and integrated with ontological approaches in order to make the decision-making process more accurate and efficient.

2 Material and Methods

The research is considered to have an applied nature, with a qualitative approach. Its scientific objectives are exploratory, using as a technical procedure a literature review and qualitative analysis (Fig. 1).

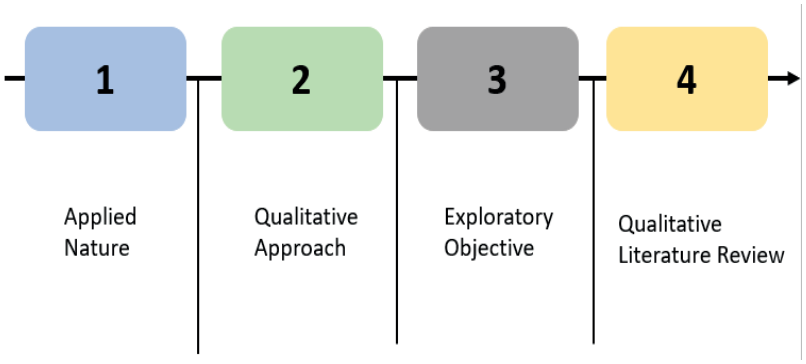

Fig. 1. Research Methodology.

The research has as its starting point a literature review on issues on the context of Reconfigurable Manufacturing Systems, such as, agility in the reconfiguration process, Semantic Interoperability such as Requirement Interpretation and knowledge representation, and Multicriteria Decision models. The goal is to establish a conceptual link between the studied areas as well as to improve understanding of the tools used in each theme and their intricate relations (Fig 2). The result of this process is a discussion on the themes, represented through a schema, which serves as the starting point to expose the current issues regarding the continuous development and flexibilization of reconfigurable manufacturing models, and their impacts in Industry 4.0.

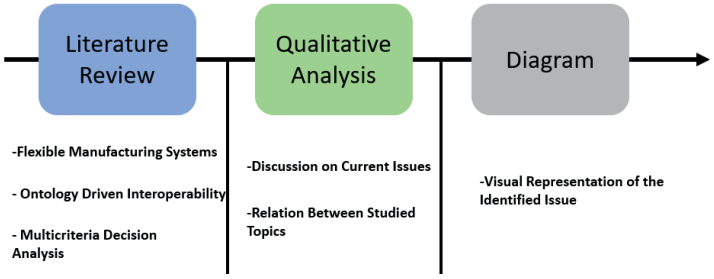

Fig. 2. Technical Procedures.

3 Related Works

3.1 Ontology Based Interoperability

Semantic interoperability is the ability of heterogeneous computer systems to share data with clear meaning. Therefore, it is concerned with the simultaneous transmission of the meaning of the data alongside it. This is accomplished though the addition of data about the data, which links each data element to a controlled, shared vocabulary. The meaning of the data is transmitted with the data itself, in one "information package" that is independent of any information system.

Since the introduction of the Semantic Web concept by [4] there has been numerous researches and applications of the W3C (World Wide Web Consortium, W3C) standards to provide web-scale semantic data exchange, federation, and inferencing capacities. Nowadays ontologies are one of the most popular tools for representing and sharing knowledge across different systems and domains [5].

The construction of ontologies is a viable solution on the formalization of these common information models and on the sharing of the formal information throughout the stages of the product development process, which, consequently, provides increased knowledge in the domains of application [6][7].

An Ontology is defined as "a lexicon of specialized terminology along with some specification of the meaning of terms on the lexicon" [7] [8] where the lexicon is the vocabulary of a knowledge domain. In this way, a significant differentiation can be made between ontologies by their degree of expressiveness. In this differentiation, simple ontologies, which formalizes only a taxonomy of concepts and basic relations between them are referred to as lightweight ontologies. When a lightweight ontology is enriched through the insertion of axioms in the form of constraints, they are classified as a heavyweight ontology. Nevertheless, the use of ontologies is restricted to the purpose of its application, that is, the knowledge structure formalized in an ontology has little reusability outside the scope of its application [8].

Given two different classification systems, a simple query finds all the data corresponding to a term in both information sources; however, this query can only be efficiently answered if both systems have their semantics well understood. If these systems are conceptualized in two different ontologies, the comparison of terms is a challenge due to the high variation of the detail level and logic between these ontologies [8][9]. To solve this limitation a shared ontology approach can be adopted, which enables terminological reasoning over the definition of classes in the descriptive logic ontologies by considering the axioms, set of relations and set of class definitions defined in the shared ontology [8][9].

Also, according to [10] and created digital links between virtual models improving the information sharing in the operation management. Similarly, [11] created a interoperable environment through the integration of different ontologies which resulted in dynamic collaborations between partners in heterogeneous and multi sited projects.
[11] affirms that with the rapid advanced and development of semantic technologies based on ontologies, there has been a shift towards more complex and better semantic modeling of manufacturing processes. This process culminates in the insertion of machining features in the semantic technologies in order to retrieve the considerable machining knowledge and shape semantics presented in these features.

[12], in the other hand, identifies that ontology based systems can be used for the optimization of machine fault diagnostics as this is a multi-disciplinary problem and the use of semantic mapping techniques and knowledge reasoning technologies can efficiently represent and organize fault knowledge with explicit and consistent semantic support. According to [12] these types of systems have the ability of supporting, sharing and scaling the fault knowledge presented in the system. [13] asserts that the ontology technology has great advantages in improving semantic consistency of multi-source heterogeneous data. However, for complex dynamic decision-making problems, there

are some limitations in the mining of ontology relations and the establishment of inference rules.

3.2 Multi-Criteria Decision Analysis

As globalization, collaboration, and cooperation contribute to a more connected and integrated competitive environment for the manufacturing industries, they have also made the decision-making process more complex whilst reducing the time for the decision made to be relevant.

In this context, the Multi-Criteria Decision Making (MCDM) methods are gaining importance as potential tools for analyzing complex real problems. This happens due to the inherent ability of these methods to judge different alternatives through several criteria (attributes) in order to provide the most suitable alternative. These alternatives may be further explored in-depth for their final implementation (Chung & Ng,2016). A MCDM problem can be concisely expressed in a decision matrix as shown in Fig 3.

		Criteria			
Alternatives		C_1	C_2	.....	C_n
	A_1	X_{11}	X_{12}	.....	X_{1n}
	A_2	X_{21}	X_{22}	.....	X_{2n}
	.....	.....	.....	.....	.....
	A_m	X_{m1}	X_{m2}	.....	X_{mn}

Fig. 3. Multi-Criteria Decision Analysis Generic Decision Matrix.

In this matrix each element (xij) represent the performance rating of "**m**th" alternative in respect to "**n**th" criteria, while considering also the significance of nth criteria [14]. This acquirement of the importance of each attribute, also called as weight of the attribute, is what boosted the introduction of numerous MCDM methods during the last decades.

Over the last decades, several MCDM methods have been proposed, the most popular of which are AHP (Analytic Hierarchy Process) [14-16], ANP (Analytic Network Process) [5], TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [17–20], ELECTRE (ELimination and Choice Expressing REality) [21–23], and PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) [24–26].

These methods have been used to aid the decision making in several fields of knowledge, such as medicine, management and logistics, among others. This can be seen with the research of [26] which creates a systematic literature review on the use of MCDM in the optimization of supply chains and concludes that there are various combined approaches for supplier selection. However, integrated AHP approaches are more prevalent. The popularity of this type of approach is due to its simplicity, ease of use,

and great flexibility. [26] creates a novel multi criteria model for the optimization of flexible manufacturing systems.

The MCDM methods' task is to support a decision-maker in choosing the most preferable variant from many possible options, taking into account a multitude of criteria characterizing acceptability of individual decision variants [43]. MCDM problems can be divided into 2 main categories: i) continuous problems and ii) discrete problems. The second type of MCDM problems can be solved either through utility functions or outranking methods [44]. Also, according to [44] the utility approach determines a relationship between the alternatives which can be indifferent and preference of one alternative over another, this has the consequence of the methods in this group leaving out the non-comparability of the decision criteria and assume transitivity and completeness of preference [29].

On the other hand, outranking methods expand the basic set of preferential situations with the relationships they create which can be: i) indifferent; ii) weak preference; iii) strict preference and iv) incomparability. In this method the preferential situations are combined in an outranking relation [45].

Furthermore, MCDM methods can vary according to their operational approaches: : i) aggregation to a single criterion (American school); ii) aggregation by using the outranking relationship (European school) [46]. However, the mixed approach which combine elements of American and European decision-making schools have gained highlight in the scientific and industrial environments [47]. According to [47] an example of this mixed approach is the Pairwise Criterion Comparison Approach methods. Lastly MCDM methods can be differentiated according to the nature and characteristics of the used data, which will immensely affect the measurement scale. Data can be quantitative or qualitative and can be expressed in the cardinal (quantitative) or ordinal (qualitative) scale [48].

3.3 Flexible Manufacturing

The introduction of a new technology in a company's operations changes the organizational structures, processes and resources, factors that present themselves as obstacles in the decision phase and in the implementation of these new technologies. Currently, the choice of advanced manufacturing technologies is made through operational criteria such as productivity and performance, which can offer a competitive advantage and, therefore, must be chosen according to strategic criteria. [27]. The main characteristic of advanced manufacturing technologies is their flexibility (to produce a wide variety of products on a small scale without having extra costs or penalties) is pointed out by several authors [3][27][28][29].

Advanced manufacturing systems are systems that use mechanical, electronic and computational subsystems to operate and control production, encompassing a large set of machines that execute, monitor and connect the production processes [30]. The same author emphasizes that the adoption of advanced manufacturing technologies is a key condition for maintaining the company's competitiveness in the long term. Nevertheless, many advanced manufacturing implementation projects fail to be more significant in small and medium-sized companies, as the managers of these companies are the ones

who most want to implement these technologies, but they do so from instinct or information from similar companies.

Yet, [3], states in his research that small and medium-sized companies do not wish to implement, or do not understand how these technologies could assist them in improving customer satisfaction and market results. The author also states that these companies have limited financial and human resources, preventing these companies from implementing complex technological systems.

Over the past two decades, there have been reports of improvements in flexibility, quality and productivity in industries caused by the use of advanced manufacturing technologies [31][32]. [33] claim that advanced manufacturing technologies can effectively assist the length of manufacturing objectives and simultaneously consider competitive objectives and manufacturing decision areas, being considered resources mobilized for the construction of competencies. [3] stated that with the growing emphasis on flexibility to ensure a company's long-term competitiveness, the relationship between advanced manufacturing technologies has taken on an important place for decision making. In addition, the higher the level of advanced manufacturing technologies and enterprise control technologies, the greater the level of flexibility in manufacturing.

From the many flexible manufacturing technologies additive manufacturing has been prominent in both industry and academia, as it has benefits compared to traditional manufacturing models, such as geometric flexibility as well as a potential to reduce the time and cost of manufacturing products [34].

Reconfigurable manufacturing systems (RMSs) was first proposed by the Engineering Research Center of the University of Michigan in1999[29]. Though the use of these systems manufacturers could make multiple variations of customized products at the price of standardized mass products [29][35]. [29][36] analyzed the characteristics of RMS in detail and found out that the most used approaches are biological manufacturing systems (BMSs) and holonic manufacturing systems (HMSs). The reconfiguration methods could be classified into two categories: i) knowledge-based reasoning methods; ii) artificial intelligence-based optimization methods [29]. The knowledge automation technologies of RMS have attracted considerable interest. [29][37] proposed an ontology-based agent approach with the goal of fast reconfiguration of modular manufacturing systems. Furthermore, [29] [37–39] proposed the combination of knowledge-based reasoning methods with periodic inspection for the dynamic and automatic reconfiguration of systems.

For the second kind, optimal reconfiguration of manufacturing systems needs the use of advanced artificial intelligence techniques, such as deep learning and big data [40]. However, these conventional optimization methods for RMS suffers from substantial computation complexity, which hinders rapid and online reconfiguration of the manufacturing system.

There are three significant problems in current RMS. Firstly, essential measurement factors, including the scalability and reconfigurability of the current systems, which needs to be considered during the design process of the RMSs [41][42]. Secondly, current RMS realizes control logic validation with software testing after the mechanical structure reconfiguration is assembled, which will take a significant amount of time to do and is susceptible to reconfiguration mistakes. Thirdly, dealing with the rapid

reconfiguration of the manufacturing system, requires not only a digital twin architecture as a foundation but also an optimization method. These issues mean that the complex balancing and coupling relationship between the system productivity and reconfiguration cost is difficult to model in the environment of the frequent change.

4 Discussion

This research works towards finding evidence that demonstrates the current issues regarding semantic interoperability and Multi-Criteria Decision-Making methods in an advanced manufacturing environment. These issues provide sustenance to the proposal of an ontology and MCDM integration model that aims to aid the real time reconfiguration and decision making in flexible manufacturing processes in order to ensure higher quality products and increase agility of the manufacturing process.

The mapping of the current issues revealed the limitations of a ontology driven interoperability system when it is used in a highly mutable environment, and, also, how the sharing of ambiguous information in such an environment can reduce the competitiveness of an enterprise as it will difficult the decision making process, raising costs and diminishing the products quality.

The MCDM models can be associated with ontological approaches as aids for the reasoning presented in them. The application of MCDM algorithms in these approaches create case-based reasoning techniques, which can aid in the flexibilization of the ontological structure and consequently promote a more accurate and efficient decision-making process. These concepts may be used integrated with ontology-based interoperability models in order to create a flexible decision-making environment that can aid in the reconfiguration of an advanced manufacturing system allowing for a more agile process and ensuring the product`s quality. Fig. 4 highlights the relationship of the concepts that this research approached. From the figure can be seen the decision making in a flexible manufacturing environment can be divided into three main layers. The outmost layer regards the multi-criteria analysis, while the second involves the main systems in a flexible manufacturing system and finally the decision-making layer.

The multicriteria analysis layer consists in the analysis of the many heterogeneous requirements that come from the consumer and from the enterprise. These requirements range from desired finishing qualities from the consumer to material handling and stock logistics from the enterprise. As these requirements come from various sources, they may present semantic homogeneity issues which can lead to a wrongfully interpreted information that consequently will prejudice the decision-making process and the reconfiguration of the manufacturing system.

The flexible manufacturing layer encompasses the flexible manufacturing system, from the material handling system to the working machines and the main control system. This layer consists in the capability and restrictions presented in the subsystems of the manufacturing process. These restrictions combined with the requirements of the multicriteria analysis layer make the information form that will guide the decision-making process.

However, the restrictions presented by the flexible manufacturing layer can cause misunderstanding or may present semantic conflicts with one another or even with the requirements from the multicriteria analysis layer. These misunderstandings and conflicts may hinder the decision-making process that consequently impoverishes the manufacturing quality and thwarts the flexibility of the overall production process.

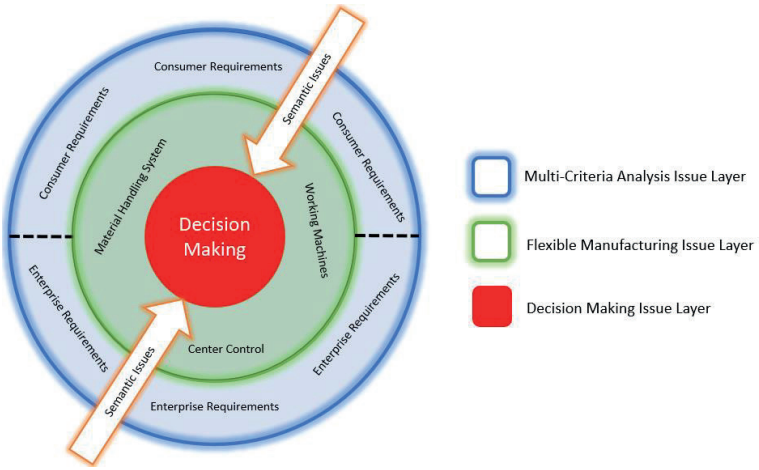

Fig. 4. Representation of Current Issues.

Finally, the decision making layer defines the decision making process, with the interpretation of the requirements and restrictions of the outwards layers and reconfiguring the manufacturing systems and processes in order to attend the requirements and generate the most value possible to the consumer and the enterprise. This process can be hindered with semantic heterogeneity issues from the other layer, while being susceptible to semantic errors in the decision making process which can compromise the timely reconfiguration of the manufacturing system that will in turn compromise the value generation and the attendance of the requirements and restrictions.

5 Conclusion

This paper presented a research that lead to the development of a model which shows some of the critical issues that hinder the development of a real time process reconfiguration environment. These areas are essential to ensure a competitive position for an enterprise in the global competitive environment it is inserted.

The standardized and formalized knowledge that is captured by an ontology driven system allows it to be retrieved, shared and reused in different stages of the reconfiguration process and, also, through the process of relating concepts, the information can be captured in its entirety as well as extended as the need arises.

Multicriteria decision analysis models have gained focus of the scientific and industrial communities as a support tool for the decision-making process in the product development and manufacturing as these processes excel in environments with numerous and conflicting alternatives, providing the optimal alternative. In this context, the multicriteria decision analysis makes for more consistent decision making as subjectivity and possible trade-offs can be contextualized and incorporated into these models. With these characteristics the multicriteria decision analysis can be incorporated and integrated with ontological approaches in order to make the decision-making process more accurate and efficient.

In order to continue this research several subjects are proposed for future works. The integration of MCDM methods with ontological applications and map the decision criteria needed for an advanced manufacturing reconfiguration process in order to develop an application ontology to aid in the reconfiguration process are some research perspectives.

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Estudio de Caso sobre el Cumplimiento de los Principios de Gestión de la Calidad Según la Norma ISO 9001 Versiones 2008 y 2015, de los Empleados de Dos Empresas Cafeteras de Nariño Colombia.

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Resumen. Esta investigación evaluó el nivel de cumplimiento de los principios de gestión de la calidad percibidos por los empleados de dos empresas cafeteras: una de ellas certificada y la otra sin certificar, ubicadas en la ciudad de Pasto en Nariño, Colombia. La evaluación se fundamentó en los principios definidos en la norma ISO 9001 versión 2008 y comparó los resultados con la versión 2015. Además de analizar si existían variaciones en la percepción de los principios de gestión de la calidad, se evaluó si al actualizarse la versión de la norma ISO 9001, la percepción sobre los principios de calidad cambió e incidió en la implementación, debido a que son la base para el funcionamiento eficiente y eficaz de un sistema de gestión de la calidad. Para realizar el comparativo entre las empresas se usó un estudio cuantitativo con diseño no experimental, exploratorio, descriptivo, observacional, transversal, sobre unidades independientes de investigación, correspondiendo, por tanto, a un estudio de casos en relación con la selección intencionada de la unidad de análisis. Para evaluar la percepción, se aplicó un instrumento de medición de tipo encuesta validado y aplicado previamente. Para la revisión de la norma ISO 9001, se hizo un análisis comparativo entre las versiones 2008 y 2015. Los resultados obtenidos mostraron diferencias en la percepción de los principios de la gestión de la calidad, principalmente los denominados: enfoque en procesos, liderazgo, participación del personal y enfoque al cliente por parte de los empleados de cada empresa.

Palabras clave: Certificación, ISO 9001:2015, ISO 9001:2008.

1 Introducción

Los cambios introducidos por la Norma ISO 9001:2015 pueden afectar la percepción de los principios de calidad para aquellos usuarios previamente certificados con la Norma ISO 9001:2008, la cual identificaba ocho principios para mejorar continuamente el desempeño. La actual versión de ISO 9001:2015 eliminó el principio de "Enfoque de Sistemas", aunque éste sigue implícito en la norma. Los principios de la norma son la base para desarrollar un Sistema de Gestión de la Calidad adecuado a las necesidades del cliente y para la mejora interna constante de los procesos de una organización [22]. De igual forma, los estudios comparativos entre empresas certificadas y no certificadas son escasas, no encontrándose publicaciones en el sector cafetero en bases de datos WoS, Scopus y ScIELO revisadas, pero sí en otros sectores (Brito et al, 2020; Dellana et al 2020; Heras-Saizarbitoria et al, 2015; Tamayo-Torres et al, 2014, Caro Et al, 2009; Martinez Costa y Martinez Lorente, 2003), o entre empresas no certificadas (Ghose y Roy, 2020).

El presente estudio utilizó como variables de medición, los principios de la ISO 9001:2008, que son: enfoque al cliente, liderazgo, participación del personal, enfoque basado en procesos, enfoque en sistemas, mejora continua, relación con los proveedores, enfoque en hechos. Estas variables fueron utilizadas para evaluar el nivel de cumplimiento de los principios de gestión de la calidad percibidos por los empleados de dos empresas cafeteras colombianas, una certificada y una no certificada, y posteriormente, para comparar dichos resultados con la ISO 9001:2015.

El objetivo de la implementación de sistemas de gestión de la calidad es la mejora continua de los procesos, productos y servicios lo que permite la satisfacción de los clientes y el fortalecimiento de la responsabilidad de la organización [1. Por otro lado, las organizaciones implementan los sistemas de gestión de la calidad para demostrar la capacidad de proporcionar productos y servicios acordes a los requisitos del cliente [46]. Los beneficios obtenidos por las empresas posterior a la certificación ISO 9001, pueden verse mejorados o disminuidos de acuerdo con algunos factores tales como: a) motivación de la empresa por adoptar el modelo; b) la formación y educación continua de las personas permite sostener y mejorar el sistema; c) el permanente cumplimiento de los principios de gestión de calidad, que son el fundamento del sistema[5]. Es importante incluir el mantenimiento de los sistemas de gestión de la calidad dentro de los aspectos que generan efectos positivos en la productividad y la mejora de la calidad de los procesos. El marco de gestión de mantenimiento basado en siete cualidades de los principios de gestión puede ayudar a una organización a: aumentar la producción con los mismos activos, reducir la necesidad de reemplazo de capital y mejorar el rendimiento, costo y productividad, [28].

En este contexto, es de esperar que las empresas que se han certificado presenten un mayor grado de cumplimiento para todos los principios de gestión de la calidad que las empresas no certificadas; a partir de ésta fundamentación teórica, surge la necesidad de establecer la hipótesis: Los empleados de una empresa certificada según ISO 9001, perciben un mayor nivel de cumplimiento de los principios de gestión de la calidad que los de una empresa no certificada, lo que permite determinar si con el

proceso de certificación, se han incrementado los beneficios intrínsecos a la misma. Dicha hipótesis puede ser evaluada con la versión 9001:2008 o 9001:2015.

Para esta investigación se optó por un estudio de tipo mixto, cualitativo y cuantitativo con diseño no experimental con el fin de realizar una comparación de la percepción de los principios de gestión de la calidad entre los dos tipos de empresas y su interrelación por niveles jerárquicos; además, se buscaba que el instrumento diseñado midiera los principios o dimensiones de gestión de la calidad de forma relacionada para tres grupos: personas externas a la organización, liderazgo y funcionamiento interno de la organización. En este contexto, se requería el uso de métodos exploratorios y descriptivos. Para esto se realizó una recolección de datos mediante la elaboración y aplicación de instrumentos en un contexto claramente definido [30].

Se utilizó un estudio de caso, al ser una investigación de tipo cualitativa que observa de forma detallada a sujetos de estudio [42]. El uso de la investigación cualitativa tiene la ventaja de recoger y recopilar información de una muestra para aumentar la comprensión particular de un fenómeno.

2 Metodología

2.1 Material

Debido a que el estudio comenzó a finales del año 2014, cuando la última versión de la norma ISO 9001:2015 aún no estaba vigente, inicialmente se aplicó un enfoque de estudio de caso, seleccionando una empresa cafetera certificada según la norma ISO 9001:2008 y una empresa cafetera sin certificar, ambas localizadas en la Región de Nariño, Colombia; se realizó un censo en cada una de ellas, aplicando la encuesta a todos los trabajadores de las empresas. Posteriormente con la adaptación de la empresa certificada a la versión 2015, se evaluaron los cambios relacionados con los principios de calidad, entre la versión 2008 y 2015 en la empresa certificada, aplicándose un nuevo instrumento. Se aplicaron 38 encuestas en la empresa certificada y 29 encuestas en la empresa no certificada, los niveles jerárquicos a los que se aplicó la encuesta fueron directivos, constituidos por gerentes y administradores y operarios constituidos por el personal encargado del proceso, el área de empaque y almacenamiento de producto terminado.

Método

En primer lugar, se identificaron tres objetivos específicos para el estudio. Posteriormente, se realizó una caracterización de los empleados y la relación entre las variables. El estudio corresponde a una investigación de tipo cuantitativa con diseño no experimental, exploratorio, descriptivo, observacional, transversal sobre unidades independientes de investigación, correspondiendo a un estudio de casos [48] en relación con la selección intencionada de la unidad de análisis correspondientes a los empleados de ambas empresas.

Para evaluar la percepción de los niveles de cumplimiento de los principios de gestión de calidad, entre los niveles jerárquicos de la empresa cafetera certificada y no

certificada según ISO 9001:2008, se usó un análisis cuantitativo, exploratorio, descriptivo de tipo observacional.

Para evaluar la percepción de los niveles de cumplimiento de los principios de gestión de la calidad de los empleados de la empresa certificada según ISO 9001:2015, con la percepción de los empleados de la empresa no certificada, se usó un análisis cuantitativo, asociativo observacional.

Finalmente, para analizar las diferencias entre las versiones 2008 y 2015 de la norma ISO 9001, respecto a los principios de gestión de la calidad y su aplicación a nivel empresarial, se usó un análisis cualitativo, asociativo observacional.

2.2 Instrumento

El instrumento empleado registra la percepción de las dimensiones asociadas al cumplimiento de los Principios de Gestión de la Calidad; fue diseñado y validado cualitativamente en la investigación realizada por Pérez y Pérez-Luco (2010) [39] relacionado con la ISO 9001:2008; como complemento a este instrumento, se utilizó la norma ISO 9001:2015. De un universo de 12 empresas cafeteras de Nariño Colombia invitadas para la aplicación del instrumento, acudieron dos, una de ellas certificada y la otra sin certificar; la encuesta se aplicó mediante censo a un total de 67 empleados; los resultados se evaluaron mediante un análisis porcentual que permitió determinar cuantitativamente la percepción de los principios de gestión de la calidad en cada una de las organizaciones [11].

El instrumento aplicado contó con 40 preguntas en total, 5 preguntas para cada uno de los ocho principios de los sistemas de gestión de la calidad, como se muestra en la Tabla 1.

A partir de los ocho principios de la gestión de la calidad, se obtuvieron puntajes máximos y porcentajes de cumplimiento en cada principio por empresa y por nivel jerárquico. Para analizar los resultados obtenidos de la aplicación de la encuesta, se codificó la escala de tipo Likert de la siguiente manera: 0 nunca, 1 casi nunca, 2 regularmente, 3 casi siempre, 4 siempre. Teniendo en cuanta que por cada principio hay 5 preguntas y que la valoración máxima en la escala de Likert para cada pregunta es de 4, el puntaje máximo a obtener para cada uno de los ocho principios es de 20 puntos, lo que representa el 100% de cumplimiento del principio. A partir de este análisis se realizaron los cálculos de porcentaje de cumplimiento en cada empresa y en cada nivel jerárquico.

En los resultados se presentan los promedios de puntaje total por tipo de empresa y nivel jerárquico y su expresión en porcentaje en relación con el puntaje máximo posible a partir de la codificación de la escala de Likert.

A continuación se representa el instrumento empleado para recolectar la información.

3 Resultados y Discusión

La implementación de ISO 9001 en sus diferentes versiones en empresas cafeteras no es común en Latinoamérica, aunque algunos estudios en otros países se han enfocado en implementar la norma para mejorar la calidad de los procesos [38]. En Colombia, se ha estudiado el efecto de implementar sistemas de gestión en empresas procesadoras de café [11] y del desempeño de algunas empresas [4].

Para realizar este estudio de caso, se analizó en forma censal una población objetivo de 67 empleados, de los cuales 38 pertenecen a la empresa certificada y 29 a la empresa no certificada. Se logró encuestar al 100% de la población objetivo, donde el 32.84% corresponde al nivel jerárquico directivo, de los cuales el 81.82% cuentan con educación superior. En la población total bajo estudio, el 44.44% de los operarios cuenta con educación superior.

Al comparar los instrumentos de medición en el modelo para la versión 2015 de la norma ISO 9001, se encontró que la mayoría de preguntas era aplicable para los principios actuales debido a su similitud, diferenciándose principalmente en el principio "enfoque basado en procesos", que actualmente engloba lo que en la versión 2008 estaba contenido en dos principios, "enfoque basado en procesos" y "enfoque de sistema para la gestión"; además, se encuentra presente en el principio de la versión actual de "Gestión de las relaciones", que aunque comparte aspectos con el principio de la versión 2008 "Relaciones mutuamente beneficiosas con el proveedor", la versión actual amplía su aplicación a otras partes interesadas de la empresa, como por ejemplo los accionistas u otros grupos de interés (ISO, 2015). Se comprueba con este estudio que la organización debe familiarizarse con los principios de gestión de la calidad, y comprender sus cambios en la versión vigente, para evitar malinterpretar el nuevo requisito y cometer fallas en la implementación o ajuste del sistema de gestión [32]. Una comparación de los resultados obtenidos al aplicar el instrumento se detalla en la Tabla 1 y la Tabla 2 para directivos y operarios, respectivamente.

Tabla 1. Porcentajes de cumplimiento de los principios de gestión de la calidad según directivos, ISO 9001: 2008.

Principio	Directivos empresa certificada (%)	Directivos empresa no certificada (%)
Enfoque al cliente	77.50	70.50
Liderazgo	82.42	57
Participación del personal	84.17	58.5
Enfoque en procesos	92.50	74.5
Enfoque en sistemas	87.08	64
Mejora continua	86.25	63
Relación con los proveedores	81.67	64.5
Enfoque en hechos	87.08	64

Fuente: Autor, a partir de las encuestas realizadas.

Tabla 2. Porcentajes de cumplimiento de los principios de gestión de la calidad según operarios, ISO 9001: 2008.

Principio	Operarios empresa certificada (%)	Operarios empresa no certificada (%)
Enfoque al cliente	77.5	70
Liderazgo	87.8	57.63
Participación del personal	85.96	67.10
Enfoque en procesos	89.61	80.79
Enfoque en sistemas	84.23	75.53
Mejora continua	86.33	75
Relación con los proveedores	85.96	69.74
Enfoque en hechos	88.8	67.1

Fuente: Autor, a partir de las encuestas realizadas.

En la empresa certificada, los directivos y los operarios obtuvieron un puntaje máximo de cumplimiento en el principio "enfoque en procesos" y un puntaje mínimo en los principios "enfoque al cliente" coincidiendo con el estudio realizado por Pérez & Pérez-Luco (2010) [39], quienes señalan que los trabajadores de la empresa certificada de su estudio, percibe un mayor cumplimiento en los principios de gestión de la calidad relacionados con sistemas, procesos y productos, mientras que la menor percepción del cumplimiento se encontró en los principios relacionados con clientes, personas y liderazgo. Sin embargo, es importante notar que, debido a que el primer principio de la gestión de la calidad es el enfoque al cliente, el cual establece que las organizaciones dependen de sus clientes y por lo tanto deben comprender sus necesidades, satisfaciendo sus requisitos y esforzándose por exceder sus expectativas [33], este aspecto debería arrojar resultados altos en la empresa certificada. Una percepción baja del principio enfoque al cliente se relaciona con la imagen corporativa y la satisfacción del cliente, [17] en su análisis de la percepción de los clientes respecto a la calidad del servicio recibido, quien analizó los factores que determinan la satisfacción o insatisfacción de clientes y encontró que "… el servicio que presta el personal encargado de la atención al cliente es un aspecto crítico en la evaluación de la calidad del servicio".

Una discriminación gráfica de los resultados relacionados con la percepción evaluada se encuentra en la Figura 1, donde se observa mayor puntaje para los directivos que para los operarios, como era esperado.

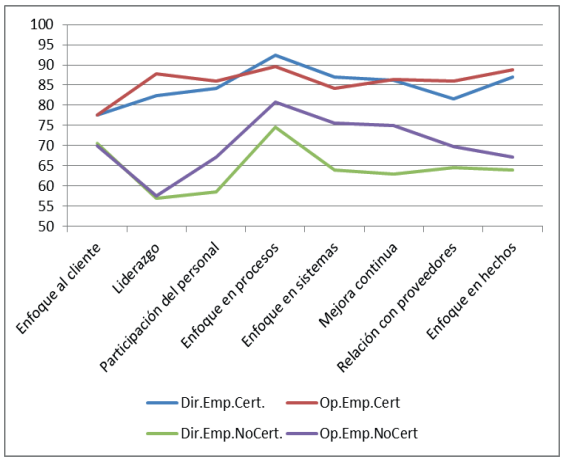

Fig 1. Empresa Certificada y No Certificada. Gráfico de percepción de cumplimiento (%) ISO 9001:2008.
Fuente: Autor

En la empresa no certificada, los directivos y operarios obtuvieron un puntaje máximo de cumplimiento en el principio "enfoque en procesos" y un puntaje mínimo en el principio "liderazgo", seguido por el principio "participación del personal"; se infiere que esto se debe a que en las empresas certificadas el personal de todos los niveles de la empresa debe involucrarse totalmente en el logro de los objetivos de la organización mediante una cadena de participación y comunicación.

Respecto a la participación del personal, en la empresa no certificada se observó un nivel bajo, relacionado principalmente con dos factores: inexistencia de un plan de incentivos y falta de reconocimientos para motivar al personal hacia la participación y el liderazgo. Los resultados se pueden observar en la Tabla 3.

Tabla 3. Comparación de los puntajes de cumplimiento de los principios de gestión de la calidad entre la empresa certificada y no certificada.ISO 9001:2008.

Total puntaje por empresa

Empleados	Puntaje	Porcentaje %
Directivos certificada	136.33	85.2%
Directivos no certificada	103.2	64.5 %
Diferencia directivos certificada y no certificada	33.13	20.7%
Operarios certificada	137.27	85.8 %

Operarios empresa **no certificada**	112.59	70.4%
Diferencia operarios certificada y no certificada	24.68	15.43 %

Fuente: Autor a partir de las encuestas realizadas.

Tanto en la empresa certificada como en la empresa no certificada, los directivos y los operarios obtuvieron un puntaje máximo de cumplimiento en el principio de gestión de la calidad denominado "enfoque en procesos"; sin embargo, en la empresa certificada los porcentajes de cumplimiento en este principio fueron mayores que en la empresa no certificada, lo que indica que en la empresa certificada existe un mayor entendimiento y gestión de las actividades como procesos interrelacionados y coherentes, lo que posibilita la optimización del rendimiento de la organización.

En la empresa certificada y en la empresa no certificada los puntajes mínimos se obtuvieron en los principios relacionados con personas. En este contexto, en la empresa certificada los menores puntajes se obtuvieron en los principios relacionados con personas externas a la organización (enfoque al cliente y gestión de las relaciones). Por otra parte, en la empresa no certificada los puntajes mínimos se obtuvieron en los principios relacionados con personas internas a la organización (liderazgo y participación del personal).

A continuación, en las tablas 4, 5, 6 y 7, se analiza cada uno de los principios de calidad de acuerdo a las versiones 2008 y 2015 de la norma ISO 9001, relacionando las preguntas realizadas y validadas previamente. Como se podrá observar, en la versión de 2015, no hubo cambios grandes en los principios de "Liderazgo" y "Enfoque en procesos". Hubo cambios intermedios en los principios "Participación del personal" y "Enfoque basado en hechos". Sin embargo se realizaron cambios relevantes en los principios de "Enfoque al cliente", "Mejora Continua" y "Relación mutuamente beneficiosa con el proveedor", principalmente debido a que el nuevo enfoque, busca que la empresa involucre de forma mas distintiva, además de los clientes receptores del producto a otros grupos de interés, que la empresa debe identificar como relevantes para lograr sus objetivos de calidad, adicionalmente la ISO 9001:2015 se orienta mas a un contexto estratégico que contempla un análisis externo mas profundo, que abarca no solo mejoras internas, sino estrategias que involucran el entorno empresarial, la identificación y prevención de riesgos.

El principio de "Enfoque en Sistemas" se eliminó debido a que se consideró inmerso en las interacciones de los elementos del sistema.

Tabla 4. Relación principios de las versiones 2008 y 2015 de la norma ISO 9001.

Principio de Gestión de Calidad ISO 9001:2008	Pregunta del instrumento relacinada con la norma ISO 9001:2008	Principio de Gestión de Calidad ISO 9001:2015	Pregunta relacinada con la norma ISO ISO 9001:2015 / Cambio
1.Enfoque al cliente	P.1 Existen reclamos de los clientes hacia la empresa P.13 Me interesa mucho satisfacer los requerimientos de los clientes P.21 Los clientes tienen una buena percepción de la empresa P.29 La Empresa tiene buena comunicación con sus clientes P.33 Yo sé lo que los clientes requieren de esta empresa	Enfoque al cliente	Preguntas: Igual que en la versión 2008, las preguntas: P.1, P.13,P.21, P.29, P.33 Cambio: Se incluye el concepto de partes interesadas, que además de los clientes, son grupos capaces de impulsar o frenar la satisfacción del cliente, se destaca mayormente en las sesiones 4.3, 5.2.2 , 8.3.2 , 9.3.2 de la norma ISO 9001:2015.
2.Liderazgo	P.2 La Gerencia entrega directrices claras respecto al quehacer rutinario de la empresa P.12 La Gerencia se esfuerza mucho en enseñarnos sobre cómo llegar a cumplir los objetivos de calidad propuestos P.20 La Gerencia nos motiva fuertemente a comprometernos con la calidad P.28 La Política de Calidad de la empresa orienta nuestros esfuerzos hacia un mismo objetivo P.34 Los objetivos de la calidad de la empresa son bien conocidos por todos	Liderazgo	Preguntas: Igual que en la versión 2008, las preguntas: P.2, P.12,P.20, P.28, P.34 Cambio: No hubo cambios importantes.

Fuente: Análisis a partir de encuentas, norma ISO 9001 versiónes 2008 y 2015 [24, 25]

Tabla 5. Continuación 1, relación principios de las versiones 2008 y 2015 de la norma ISO 9001.

Principio de Gestión de Calidad ISO 9001:2008	Pregunta relacinada con la norma ISO 9001:2008	Principio de Gestión de Calidad ISO 9001:2015	Pregunta relacinada con la norma ISO ISO 9001:2015 / Cambio
3.Participación del personal	P.3 En esta empresa se reconoce y estimula la iniciativa y el trabajo bien hecho P.11 Todo el personal se siente muy comprometido con la empresa. P.19 Esta empresa entrega los conocimientos para que las personas desarrollen en buena forma su trabajo P.27 En esta empresa todos nos sentimos partícipes de sus logros y beneficios P.35 La empresa invierte permanentemente en la formación y perfeccionamiento de sus empleados	Participación del personal.	Preguntas: Igual que en la versión 2008, las preguntas: P.3, P.11,P.19, P.27, P.35. Cambio: En la nueva versión es similar, aunque da mayor relevancia a la competencia y toma de conciencia, además incluye de forma mas clara a las personas externas que realizan trabajos que pueden afectar la conformidad del producto.
4. Enfoque en procesos	P.4 Conozco los insumos de entrada para mi proceso P.10 Sé cuál debe ser el resultado de mi proceso P.18 En caso de desviaciones en mi proceso sé lo que tengo que hacer P.26 Sé cuál es la secuencia de las actividades de mi proceso P.36 Sé muy bien cuáles son los aspectos que debo controlar de mi proceso	Enfoque en procesos	Preguntas: Igual que en la versión 2008, las preguntas: P.4, P.10,P.18, P.26, P.36. Cambio: No hubo cambios importantes.

Fuente: Análisis a partir de encuentas, norma ISO 9001 versiónes 2008 y 2015 [24, 25]

Tabla 6. Continuación 2, relación principios de las versiones 2008 y 2015 de la norma ISO

Principio de Gestión de Calidad ISO 9001:2008	Pregunta relacinada con la norma ISO 9001:2008	Principio de Gestión de Calidad ISO 9001:2015	Pregunta relacinada con la norma ISO ISO 9001:2015 / Cambio
5. Enfoque en Sistemas	P.5 En esta empresa siempre se cumple con lo planificado P.9 Conozco cómo influye la calidad de mi proceso en los demás procesos que se realizan dentro de la empresa. P.17 La estructura organizacional de esta empresa es difundida para el conocimiento del personal P.25 La relación entre las distintas áreas de la empresa es fluida. P.37 Los recursos están disponibles oportunamente para el desarrollo de mi proceso	Enfoque en Sistemas	Se eliminó, ya que según la nueva versión, éste principio sería un poco redundante, ya que el concepto estaría inmerso en todos los elementos que interactuan en el sistema de gestión.
6. Mejora Continua	P.6 En esta empresa los problemas y/o errores se usan para mejorar los procesos P.16 En esta empresa se evita la repetición de un problema o error P.24 Es muy importante para mi colaborar en la mejora de la actividad en que participo P.32 En esta empresa se mejoran los métodos de trabajo para prevenir problemas futuros P.38 Los aportes de los empleados ha ayudado a mejorar la calidad de los productos y servicios de la empresa	Mejora	Preguntas: Igual que en la versión 2008, las preguntas: P.6, P.16,P.24, P.32, P.38, es necesario profundizar en elementos estratégicos. Cambio: Reemplaza el concepto de "mejora continua" por el de "mejora", ya que el primero hace énfasis en optimizar el rendimiento al interior de la organización, pero el segundo involucra además de lo interno, un análisis estratégico total, que se relaciona también con el concepto de prevención de riesgo.

Fuente: Análisis a partir de encuentas, norma ISO 9001 versiónes 2008 y 2015 [24, 25]

Tabla 7. Continuación 3, relación principios de las versiones 2008 y 2015 de la norma ISO

Principio de Gestión de Calidad ISO 9001:2008	Pregunta relacinada con la norma ISO 9001:2008	Principio de Gestión de Calidad ISO 9001:2015	Pregunta relacinada con la norma ISO ISO 9001:2015 / Cambio
7.Relación mutuamente beneficiosa con el proveedor	P.8 La empresa evalúa periódicamente a sus proveedores P.14 La empresa explica claramente a los proveedores qué necesita de ellos P.22 La empresa siempre informa a sus proveedores de las calificaciones obtenidas por ellos P.30 La empresa mantiene buenas relaciones con sus proveedores P.40 Los proveedores siempre cumplen con la calidad requerida	Gestión de las relaciones	Preguntas: Aplican las preguntas de proveedores, igual que en la versión 2008, las preguntas: P.8, P.14,P.22, P.30, P.40, es necesario abarcar otras partes interesadas, de acuerdo a la definición que la empresa haga específicamente, de los grupos que pueden afectar el cumplimiento de objetivos estratégicos. Cambio: Reemplaza el concepto de "Relación mutuamente beneficiosa con el proveedor" por el de "Gestión de las relaciones", ampliando el concepto para dar mayor relevancia a otras partes interesadas como por ejemplo: organismos gubernamentales, comunidad, etc.
8. Enfoque basado en hechos.	P.15 La empresa tiene indicadores de gestión para controlar los procesos P.23 La Gerencia maneja la información adecuada para tomar decisiones P.31 La empresa usa los resultados de los indicadores para mejorar la calidad de los procesos y del producto P.39 La Gerencia toma las decisiones importantes con base en la información generada en las diferentes áreas de trabajo P.7 Conozco el cumplimiento de metas de mi área de trabajo	Toma de decisiones basada en evidencia	Preguntas: Igual que en la versión 2008, las preguntas: P.15, P.23,P.31, P.39, P.7 Cambio: Reemplaza el nombre "Enfoque basado en hechos" por "Toma de decisiones basada en evidencia", aunque internamente no hubo cambios grandes, la nueva versión ayuda a entender mejor la relevancia de basar las decisiones en evidencia, teniendo en cuenta las fuentes, documentación e interpretación.

Fuente: Análisis a partir de encuentas, norma ISO 9001 versiónes 2008 y 2015 [24, 25]

4. Conclusiones

El presente estudio además de realizar un comparativo entre empresas certificadas y no certificadas, también permitió equiparar las dos últimas versiones de la norma ISO 9001 año 2008 y año 2015, concluyendo que, aunque en el contenido de la norma actual existen algunos cambios sustanciales, respecto a los principios de calidad las diferencias de percepción son mínimas.

Los principios de calidad que más cambios tuvieron entre las versiones 9001:2008 y la 9001:20015son: el enfoque basado en procesos y la gestión de las relaciones, convirtiéndose en una visión más amplia de sistema y grupos de interés para la empresa.

Los directivos de la empresa certificada presentan un 20.71% más, de cumplimiento en todos los principios de gestión de la calidad que los directivos de la empresa no certificada y los operarios de la empresa certificada presentan un 15.42% más, de cumplimiento que los empleados de la empresa no certificada, lo que confirma la hipótesis formulada: "los empleados de la empresa certificada con ISO 9001, perciben un mayor nivel de cumplimiento de los principios de gestión de la calidad".

En general, se observa que la implementación de un Sistema de Gestión de la Calidad con base en la Norma ISO 9001 en la empresa certificada permitió obtener mayores puntajes en la medición de la percepción de los principios de gestión de la calidad.

Esto permite afirmar que, a partir de la certificación, se incrementaron algunos beneficios internos tales como: el análisis y evaluación de los datos y la información para la toma de decisiones y el entendimiento de los procesos interrelacionados como un sistema.

Mediante la utilización del método de comparación de promedios ponderados a partir de la medición de los principios de gestión de la calidad de la investigación, es posible que una organización evalúe de manera sencilla si los beneficios intrínsecos a la certificación se incrementan o disminuyen. Para esto, pueden utilizar una metodología similar a la propuesta en este trabajo, ya que es adaptable a otro tipo de empresa u organización.

En la empresa certificada, los directivos y los operarios obtuvieron un puntaje máximo de cumplimiento en el principio de gestión de la calidad denominado enfoque en procesos y un puntaje mínimo en los principios enfoque al cliente y relación con proveedores; estos resultados coinciden con el estudio realizado por Pérez y Pérez-Luco (2010) [39]en Chile.

Comparando la investigación con otros estudios, se encontró que la certificación ISO mejora las percepciones de los clientes respecto a aspectos como: calidad, satisfacción e imagen corporativa y también permite obtener otros beneficios relacionados con marketing [34].

En la empresa certificada el puntaje mínimo se presentó en los principios relacionados con personas externas a la organización como clientes y proveedores, mientras que en la empresa no certificada los menores puntajes se presentaron en principios orientados hacia el interior de la organización como son participación del personal y liderazgo.

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Sistema Innovador De Producción De Agua Segura: Análisis Económico Y Comparación Con Otras Alternativas

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Abstract. Estudios recientes demostraron que en la provincia de Salta hay zonas donde diferentes poblaciones no tienen acceso a agua segura para el consumo y se abastecen de agua de fuentes superficiales sin ningún tratamiento previo (aguas turbias en la estación húmeda). Esto se traduce en los datos alarmantes que muestran la cantidad de enfermedades relacionadas con el consumo de agua contaminada, lo que afecta principalmente a los niños. Frente a este gran desafío se diseñó un sistema modular de obtención de agua segura que involucra un proceso de clarificación (usando un clarificante natural autóctono) y una desinfección por medio de ultrafiltración. En este trabajo se buscó evaluar la rentabilidad del sistema propuesto, mediante un análisis económico que incluyó los costos asociados al mismo y los ahorros en salud pública que se obtendrían. Además, se comparó el precio del litro de agua segura obtenido con otras opciones presentes en el mercado local. Así, se pudo concluir que esta alternativa tecnológica para la provisión de agua segura es rentable y competitiva.

Keywords: Agua Segura, Evaluación Económica, Tecnología Alternativa

1 Introducción

Ante la dificultad (económica, social y política) de disponer de agua potable para consumo humano aparece el concepto de agua segura. Se define como un agua libre de bacterias peligrosas, metales tóxicos disueltos, o productos químicos dañinos a la salud, y es considerada segura para beber. En Salta (provincia del noroeste argentino), el crecimiento acelerado de la población provocó que un gran número de personas se asienten en lugares donde no se encuentran disponibles los servicios básicos de agua potable y saneamiento, incrementando los problemas de salud pública con la aparición de enfermedades de origen hídrico que afectan a ancianos y niños principalmente [1]. Estas enfermedades son la segunda causa de muerte en menores de 5 años [2].

Como una solución a esta problemática se diseñó un sistema de producción de agua segura, el cual incluyó un sedimentador que utiliza un clarificante natural autóctono (mucílago de penca de tuna, *Opuntia ficus-indica miller*) y un módulo de ultrafil-

tración (UF) para desinfectar el agua [3]. El agregado de la etapa de clarificación hizo que el equipo sea más versátil y pueda ser alimentado a partir de cualquier fuente de agua superficial (turbia o no), además la UF es reconocida por su eficacia en la producción de agua segura [4,5]. Además, se realizaron ensayos microbiológicos y fisicoquímicos que verificaron la eficiencia de este proceso mediante estudios [6].

El objetivo de este trabajo fue evaluar la rentabilidad económica de este sistema de producción de agua a partir de los costos involucrados y compararlo con otras alternativas de potabilización que existen actualmente en el mercado.

2 Materiales y métodos

Se valorizó el mercado subexplotado de la penca de tuna, de donde se extrae el mucílago utilizado para clarificar el agua. Se estimó su costo tomando como base la clarificación de 100 L de agua. Se fijó un rendimiento del 78% de cada penca (extracción y utilización del mucílago húmedo), el precio de la fruta que se comercializa se estimó en $ 40 el kg, se calculó el costo de mantenimiento de las plantaciones (el 15% del costo de la fruta) y se seleccionó la dosis óptima del clarificante natural determinada previamente (0,4 g/L de agua turbia) [7]. La ventaja de utilizar un clarificante natural reside en que es un producto inocuo que no compromete la salud humana, a diferencia de las sales inorgánicas usadas convencionalmente [8], también que las poblaciones rurales tendrían un fácil acceso al mismo, por ser una planta autóctona que crece en toda la provincia de Salta [9], y que el costo del mismo sea bajo.

Luego, con el diseño del sistema de producción de agua segura [3], se determinaron los costos unitarios de cada equipo como así también los de los insumos involucrados (válvulas, bomba centrífuga, mangueras, manómetros, cartuchos de ultrafiltración, estructura metálica y accesorios varios), previendo una vida útil de 10 años. Luego de la producción diaria (200 L/d) se realiza una limpieza del sistema, por lo que fue necesario estimar también los costos de los desinfectantes involucrados (hidróxido de sodio, ácido cítrico e hipoclorito de sodio). De este modo se obtuvieron los costos anuales de producción incluyendo también los costos de limpieza. Es importante mencionar que el recambio de cartuchos de ultrafiltración se realiza cada 30 días. Se tomaron valores de boletas de facturación de Energía Eléctrica brindadas por EDESA (Empresa Distribuidora de Electricidad de Salta) para la estimación de los cargos de este tipo, de acuerdo a la potencia necesaria para la bomba funcione en el sistema. Finalmente, se calculó el costo del litro de agua segura producido por el equipo propuesto y se lo comparó con otras alternativas de provisión del recurso.

Al realizar el flujo de caja económico, al ser un proyecto de carácter social, en la inversión se consideró que se usarían los ahorros inherentes al gasto de salud pública provocados por el consumo de agua no potable. Para esto se tomó el 40% de los casos tratados de diarrea en niños de Salta Capital menores de 5 años durante el año 2018 en el Hospital Materno Infantil de Salta en Consultas, Salas de Internación Abreviada (SIA), Clínica Pediátrica y Unidades de Terapia Intensiva, arrojando un valor promedio de 267896 U$D/año. Se calcularon los indicadores económicos VAN (valor actual

neto), TIR (Tasa interna de retorno) y el período de recuperación de la inversión para evaluar la rentabilidad del proceso.

3 Resultados y discusión

El costo estimado del clarificante natural fue de 0,013 U$D/100 L de agua clarificada. Su costo es competitivo en comparación a los usados en la actualidad como clarificantes tradicionales. Particularmente el sulfato de aluminio (uno de los clarificantes más utilizados en el mercado), tiene un costo aproximado de 0,014 U$D/100 L de agua clarificada con una dosis óptima de 50 mg/L [10].

Luego de solicitar cotizaciones a diferentes proveedores, se estimó el costo unitario del equipo diseñado en 726 U$D, con una vida útil de 10 años. El valor de cada limpieza fue estimado en 16,15 U$D y al cartucho de UF (Hidrolit Abland Home Small) se le asignó un costo de $99,34 U$D, provisto por el fabricante.

El precio del litro de agua potable producido con el sistema de producción fue de 0,098 U$D/L, que convertido a pesos argentinos (con una cotización de 1U$D=45,3$, válida para abril de 2019) equivalen a 4,44 $/L. Cuando se comparó este precio con los existentes en el mercado local (Tabla 1), el mismo era aproximadamente un 41% menor, sin tener en cuenta los gastos de transporte desde las fábricas de agua potable hasta las comunidades rurales y la compra de un dispensador necesario para el cómodo abastecimiento de este recurso.

Tabla 1. Diferentes alternativas para la compra de agua segura para consumo humano.

Marca/ Empresa	Volumen (L)	Costo ($)	Precio del litro de agua ($/L)	Dispensador ($)
Ideal	20	220	11	380
Soda Mónica	20	220	11	310
3 Cerritos	20	210	10,5	300
Ivess	20	240	12	350

Cuando se realizó el flujo de caja económico para calcular los indicadores económicos, se tomó un riesgo país 900 y una inflación interanual del 51,3%. El Valor Actual Neto (VAN), la Tasa Interna de Retorno (TIR), el Retorno de Inversión (RI) y el Rendimiento del proyecto en un horizonte de 10 años (REND) fueron: VAN= U$D 300641, TIR = 63,7%, RI = 2 años y 7 días y REND = 128,33%. Como se pudo comprobar el proyecto es rentable con un óptimo rendimiento. Cabe destacar que esta propuesta no pudo ser evaluada como un proyecto de inversión económico netamente, debido a que tiene involucrado un factor social relacionado con el mejoramiento de la calidad de vida de las personas. Por esta razón se tomó como inversión el gasto de salud pública evitado que es aquel que se obtendría si las familias de Salta Capital y alrededores tuvieran acceso a agua segura. Con la inversión se podría construir en el primer año del proyecto 300 equipos de obtención de agua potable, y con la recuperación de la inversión y en el año 5, 300 equipos más, haciendo un total de 600 equipos. Estos equipos serían distribuidos en viviendas y escuelas rurales.

4 Conclusiones

Se pudo determinar la rentabilidad de la implementación del sistema de producción de agua potable y el costo del litro de agua, el cual resulta competitivo con los existentes en el mercado. También se determinaron los montos que se ahorrarían en la salud pública por la ejecución del proyecto. Sin embargo hay que tener en cuenta otros beneficios asociados al mismo que son: la disminución en morbilidad en niños por deshidratación, el aumento de productividad de las personas beneficiarias, ya que se evita la detención de la actividad laboral por motivos de salud, el impacto en contra de la desnutrición infantil, ya que el agua potable es un elemento esencial para la asimilación correcta de nutrientes y un buen desarrollo cognitivo, y otros beneficios sociales que requieren de un análisis extenso para ser medidos.

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Assessing funding options for digital transformation: a study with specialists

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Abstract. With the increasing demand for investments in innovation and digital transformation, there is a need for more detailed analysis from the practical initiatives being carried out. Government benefits have served as an incentive for companies, with governments seeking industry development and improvements in aspects that are of society's interest. The objective of this study is to verify how companies in the Brazilian automotive industry have been funding the formulation of new products and solutions in this scenario. Questions were sent to specialists from the industry and local institutions that finance and support research and development, who pointed out the following funding options: own resources; government benefits; partnerships; loans and grants; venture capital and private equity. Analyzing the options made by the industries consulted, it was possible to notice a clear difference between them. One of the companies prioritized the use of its own resources, while the other had no restrictions on the use of different options. Another difference observed is the way in which companies deal with the use of tax benefits: while one counts on the services of a consultancy company to analyze projects with the potential to recover the investment made, another company consulted does not use this type of service. Results of the study also highlight that both management guidelines and organizational culture have the potential to impact the way companies make their investments. This paper, hence, discusses these differences to provide insights related to the funding of digital transformation initiatives both for academics and practitioners.

Keywords: Innovation, Digital Transformation, Investment, Expert Consult, Automotive Industry.

1 Introduction

With the increasing demand for investments in innovative projects, which help companies to develop skills that lead to digital transformation [1], there is a need for more detailed analysis of how these initiatives have been taking place in a practical context. To carry out these investments, organizations need resources to fund the necessary initiatives, which include hiring labor and purchasing equipment and supplies, focusing on leveraging performance [2].

In relation to the automotive industry, some of these means of financing are more notorious. Large companies have a structure that makes it possible to develop new projects using their own resources, whether tangible or intangible. This investment capacity can be verified in the results presented by the organizations, which in some cases are public. Government benefits have also served as an incentive and financial complement to these initiatives, with the governments using these actions to develop the industry in certain areas, while seeking improvements in aspects that are of interest to the whole society [3]. Around the world, it is possible to verify the realization of this type of initiative in countries like Thailand [4], China [5] and Mexico [6].

2 Objectives

The main objective of this study is to carry out a listing of the methods that automotive manufacturers can use to finance investments in their projects for the creation and development of innovative projects, that meet the needs of a market that increasingly turns to the use of technology. The definition of innovation used is that of the Oslo Manual [7], which defines it as the implementation of new products, processes, marketing methods and organizational models.

To this end, a consultation was first carried out with industry specialists, which was followed by contact with professionals from other organizations that are related to the activity of resources, aiming at the identification of possible means that have not been mentioned by the industries. This turns the responses to become more comprehensive, bringing options that can be considered by other organizations in the same industry that have different characteristics from those found in the larger organizations. Another objective of this study is to perform the analysis of the responses obtained, so that patterns or discrepancies can be identified. This makes it possible to ask questions about improvements that could be made in processes such as the choice of means of financing by companies, as well as in the creation of laws that establish government incentives.

3 Method

The method chosen for the collection of information was a consultation with specialists, who, according to [8], are professionals who represent different perspectives on a given subject. The use of this method is justified by the need to obtain different points of view, not only from industries, but from other organizations that can provide support to automotive companies that may come to seek more information on project financing.

The research was divided into two stages, as described below. In the first phase, the same questions were sent by electronic correspondence to professionals from two large automotive manufacturers, with facilities in the Brazilian city of Curitiba. In order to increase the variety of responses, contact was also made with a funding agency and an industrial federation that support research and development in the same region. The consultation with professionals from the region cited is due to the fact that several companies in the automotive industry have factories in the area, which justifies the need for certain common contextual characteristics among them, and the diversity of

organizations of which the people consulted are part of allows a greater variety of possible different results, which may be more suitable for other industries in the automotive sector that are not large industries. This branch includes companies with different activities, which can vary between the supply of parts and the creation of solutions that meet the process of development, creation, and sale of vehicles.

In the second stage, the responses were then detailed and analyzed under different aspects, as follows:

• Description of each fundind method mentioned;

• Based on the data generated in the previous step, analysis of possible critical points in relation to each investment method.

4 Results

According to the responses obtained, with the five specialists consulted, it was possible to verify the existence of the following options for investments funding, as described in Table 1.

Table 1. Funding methods cited by each expert.

Origin	Expert	Funding means used/cited
Industry 1	Project manager	Partnerships with research organizations, tax benefits, use of own resources.
Industry 2	Innovation projects coordinator	Partnerships with research organizations, tax benefits, use of own resources, financing.
Government funding agency	Operations Coordinator for the Private Sector	Specific loan and financing lines, grants, investment funds.
Local industrial federation	Marketing manager	Partnerships with research organizations.
	Industrial funding coordinator	Specific financing lines.

4.1 Use of own resources

The definition of resources used in this research is based on the work of [9], who classifies them as tangible and intangible assets linked to the company, and which can vary from the employees and the physical structure of the organization, to the technology and capital used.

One of the possible options for industrial organizations is the use of these resources, which can take place in different ways. In projects for innovative products and services development, companies use this means in the expenditure of financial resources for the acquisition of items and contracting of services directed to R&D activities [10].

4.2 Tax benefits

Tax benefits are incentives provided by governments for companies to carry out certain activities, usually meeting some predetermined objective. This is one of the most used financing methods by Brazilian companies, which can be seen by the increase in its use in the last two decades [3].
An example of a benefit by the Brazilian government is the extinct Inovar-Auto, a program that granted tax credits to companies in exchange for vehicles manufacturing with the use of technology that would enable greater safety and energy efficiency, something that has become a concern of several countries [11].

4.3 Partnerships with research organizations

One type of initiative that was mentioned by several professionals was the establishment of partnerships with research organizations, for the development of processes and the creation of products and solutions. This activity can take place in two ways: these organizations can provide support through the provision of specific labor, so that projects are developed internally by companies, or else in the joint development of certain products or processes.

4.4 Loans and financing

Companies can obtain loans and financing from public and private banks, which often have specific lines for specific purposes. Data from the National Bank for Economic and Social Development [12] are public, for transparency reasons, which enabled the verification of data on loans made by the consulted automotive industries.

4.5 Grants

According to the Financier of Studies and Projects (FINEP), a Brazilian agency for the promotion of technology, grants are non-reimbursable public resources directed to the development of certain innovative products that are of public interest, but that are not receiving investments from the private sector [13]. The activities funded are research and technological development.

4.6 Venture capital and private equity

Venture Capital and Private Equity are two types of investment funds that can also be used by companies, the first of which is aimed at disruptive companies in the beginning of activity and with growth potential, while the second can be used by established companies [14]. Venture Capital fund investors seek to offer not only financial resources, but certain skills they have, which may be useful to the investee company [15].

5 Discussion

With the listing of the funding means used or cited by the organizations consulted, it was possible to perceive that some are seen as viable by a greater number of specialists, such as the use of loans and financing and partnerships with research agencies, which fund both the equipment used and manpower to carry out the projects. One of the possible justifications for this is the variety of organizations that make it possible to obtain these resources, as well as the fact that funding and research support agencies are generally specialized in meeting certain demands, such as equipment financing and new technologies development, respectively.

In relation to the differences between the automakers, the specialist from Industry 1 showed a preference for the use of its own resources, avoiding loans, while the specialist from Industry 2 showed no restrictions on the use of extern resources, like financing. Another difference observed is the way in which companies deal with the use of tax benefits: while Industry 1 has a consultancy company analyzing projects with the potential to recover the investment made, the other industry consulted does not use this type of service, carrying out the process internally. Knowledge management mechanisms could assist companies in fulfilling all necessary obligations.

In relation to the use of government incentives, the specialist at Industry 2 reported that the company was unable to use a certain benefit because it did not present profit. This fact demonstrates the need for verifying whether the benefits offered are aligned with the needs and characteristics of companies.

6 Conclusion and recommendations

The presented work focused on conducting an empirical study on the available funding means for investments in projects aimed at innovation and digital transformation, with a focus on the automotive industry. By sending questions to professionals from companies related to the research scope, it was possible to identify not only the current funding sources, but the different usage profiles of them among the companies consulted.

The differences found between the two industries can be justified by organizational and cultural aspects. Future research may turn to more specific analyzes of these differences, with the identification of the elements that influence decision making by managers.

Another topic that can be evaluated in greater detail is the process of creation of the laws related to the granting of tax benefits, so that it can be verified if there is an alignment between the requirements and procedures mentioned in the laws, and the reality of the companies that are its target audience.

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Implementação de um modelo de simulação na indústria moveleira

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Resumo. Com o crescente desenvolvimento econômico e tecnológico, as empresas estão cada vez mais descobrindo possibilidades de mercados, mas também estão encontrando mais concorrência e uma exigência maior na qualidade de seus produtos. Com o advento do *Lean Manufacturing*, muitas melhorias podem ser aplicadas no chão de fábrica, mas uma das mais efetivas é a simulação de eventos discretos. Com a simulação é possível representar com facilidade todas as etapas de estocagem, logística, fabricação e inspeção de uma entidade (matéria prima, produto semiacabado e produto final). Com a representação dos fenômenos no modelo de simulação se torna possível a identificação de qual melhor *layout*, aonde estão os gargalos, as perdas, quais estações de trabalho não estão trabalhando como deveriam, quais produtos possuem maior valor agregado. Este trabalho tem como objetivo desenvolver um modelo de simulação que represente da melhor maneira possível o setor de preparação de madeira em uma indústria moveleira. Por meio da análise dos processos produtivos que envolvem este setor, desenvolver ferramentas que possibilitem a coleta de dados do chão de fábrica, integração destes dados com o *software* de simulação e validação do modelo comparando os resultados com o histórico de produção. Posteriormente, é realizada a análise crítica do modelo, desenvolvimento das possíveis melhorias e aplicação destas no chão de fábrica. Por meio da metodologia utilizada, espera-se que o modelo atinja um elevado índice de similaridade com a realidade, proporcionando a fácil identificação dos gargalos e dando subsídios para a tomada de decisão da empresa.

Keywords: Indústria Moveleira, *Lean Manufacturing*, Simulação.

1 Introdução

A indústria mundial moveleira foi e continua sendo constituída, predominantemente, por pequenas empresas, que até os anos 50, visavam atender quase que exclusivamente ao mercado interno dos seus respectivos países. Somente a partir da década de 50 teve início o comércio internacional de móveis, consolidando-se na década de 70 [1]. Até o final do século passado, o mercado era altamente concentrado em produtores e cliente de países desenvolvidos. Já no início do século XXI, esse cenário começou a mudar

com uma notória entrada de países emergentes, como por exemplo, o Brasil, que em 2015 ocupou a 5° posição com 3,2% da produção mundial [2].

No Brasil, a indústria moveleira teve a sua evolução atrelada às mudanças que ocorreram na economia nacional. A partir de 1990, com a abertura comercial promovida pelo governo, houve grandes investimentos na compra de novos equipamentos de alta tecnologia, o que renovou o parque de máquinas do setor [3]. A partir dos anos 2000, o setor começou a apresentar um bom crescimento, principalmente voltado para as exportações. Porém o setor moveleiro brasileiro ainda se caracteriza como opção de terceirização de mão de obra e venda de matéria-prima para países desenvolvidos.

Atualmente, o setor vem investindo em melhorias tanto nos processos produtivos, quanto na qualidade de seus produtos [2]. O investimento no *design* é um dos principais objetivos hoje da indústria moveleira nacional, visando agregar valor aos seus produtos e uma participação mais atuante e independente no mercado internacional [3]. Mas, junto com ele, também são necessárias mudanças na forma de pensar e organizar o chão de fábrica [5].

O pensamento *lean*, vem de encontro com esses desafios enfrentados pela indústria moveleira. A filosofia *lean* tem como objetivo agregar maior valor ao produto, reduzindo os desperdícios. Uma organização enxuta entende o valor agregado ao cliente e foca seus processos-chave para continuamente ampliar este valor. A meta final é fornecer um valor perfeito para o cliente, por meio de um processo de criação de valor que tem como alvo "atingir zero resíduos" ou buscar o "defeito zero" [4].

Uma das principais ferramentas que dão suporte à implementação do pensamento *lean* é a simulação [5]. Por meio da simulação, é possível reproduzir todo o processo produtivo do começo ao fim. Os *softwares* de simulação utilizam conceitos desenvolvidos na metodologia enxuta, associados a modelos matemáticos e uma interface de "conversa" com o usuário. Assim, tais *softwares* permitem a identificação e análise de problemas, além de testar propostas de solução, alternativas e até realizar previsões, tornando-se um forte aliado na tomada de decisão [5].

Neste contexto, o presente trabalho tem como objetivo desenvolver um modelo de simulação que represente as atividades exercidas no setor de preparação da madeira numa fábrica moveleira, integrando, em tempo real, dados do chão de fábrica com o *software* de simulação. O *software* escolhido foi o Arena®. As informações de entrada serão coletadas, de forma *online*, a partir do banco de dados da fábrica por meio de relatórios no formato MS Excel.

2 Revisão Bibliográfica

Nesta seção, tópicos relevantes para o desenvolvimento da pesquisa são revisados. Em primeiro lugar, o conceito de *Lean Manufacturing* é abordado, visto que a filosofia enxuta se encontra como um dos principais fatores de contexto do trabalho. Em segundo lugar, conceitos de base do estudo das filas são apresentados no sentido de contextualizar a problemática abordada neste trabalho, bem como possibilitar a interpretação do comportamento das entidades submetidas à simulação. Em terceiro lugar, o conceito da

simulação de eventos discretos é explorado. Por fim, o *software* de simulação Arena® - escolhido para o desenvolvimento do trabalho - é apresentado.

2.1 O Sistema *Lean Manufacturing*

Um sistema de manufatura é constituído por máquinas, pessoas e outros recursos com o objetivo de produzir um determinado produto ou serviço. O sistema *Lean Manufacturing* tem como fundamento principal conduzir os sistemas convencionais de produção para um sistema de produção enxuto com foco na melhoria dos processos e redução das perdas. [6]

A ideia de produção enxuta tem como objetivo identificar os processos que agregam valor ao produto, alinhá-los da melhor maneira possível, aproveitando a melhor qualidade no menor tempo, sem que haja interrupções no sistema. Utilizando os insumos de maneira mais eficaz, com menos perdas, visando eliminar ou reduzir os processos que não agregam valor. Tornando o trabalho mais satisfatório, dando ênfase na qualidade, atingindo apenas a quantidade necessária no tempo adequado [7].

Um método de análise ou diagnóstico principal para atingir os objetivos da filosofia é por meio da identificação do fluxo de informação de todas as etapas do produto ou serviço. Nesse sentido, é possível identificar grandes focos de desperdício, fazer novas sugestões e apresentar alternativas para um plano de ação com as etapas que deverão ser desempenhadas para alcançar a situação ideal [8].

2.2 Estudo das Filas

É possível definir fila como o processo de acesso de entidades a uma operação, da qual a demanda é superior a capacidade de atendimento. A formação de filas se dá em razão do fluxo [9]. A Teoria das filas é definida como um ramo da probabilidade que estuda a formação de filas, por meio de análises matemáticas precisas e propriedades mensuráveis das filas. Ela provê modelos para demonstrar previamente o comportamento de um sistema que ofereça serviços cuja demanda cresce aleatoriamente, tornando possível dimensioná-lo de forma a satisfazer os clientes e ser viável economicamente para o provedor do serviço, evitando desperdícios e gargalos [10].

Se os gargalos resultam em maior tempo de espera, a qualidade e a produtividade do sistema de atendimento inteiro caem, gerando tendência de aumento do custo total desses sistemas. Porém, exceder a capacidade do sistema, de forma a eliminar as filas, também resulta em aumento nos custos operacionais. Portanto, os modelos propostos pela Teoria das filas, são importantes para auxiliarem a compreensão e análise de equilíbrio entre o tempo de espera em fila e o custo operacional [11]. A simulação é uma metodologia que tem tido sua aplicação cada vez mais expandida, especialmente em estudos de fila complexos, que devem atender um conjunto de hipóteses para o funcionamento [12].

2.3 Simulação de Eventos Discretos

A simulação computacional vem a cada ano sendo utilizada em inúmeras companhias e direcionada para diversas aplicações no processo de apoio à tomada de decisão. É possível encontrar inúmeros *softwares* de simulação que diferem em complexidade de programação, apresentação dos resultados, custos e formas de aquisição. Esses programas podem ser adaptados a diversas situações, fazendo com que esta ferramenta seja utilizada por empresas de qualquer ramo de atividade e de qualquer porte.

O uso da simulação na resolução dos problemas de filas apresenta boas vantagens em relação a outras soluções principalmente pela sua maior aplicabilidade. Outra vantagem é com relação a representação gráfica do sistema, que além de facilitar a análise e interpretação dos resultados, se caracteriza pela flexibilidade de adaptação à realidade. [13]

2.4 Software de Simulação Arena®

O *software* escolhido para o desenvolvimento deste trabalho foi o Arena®. Desenvolvido pela *System Modeling* em 1993. Graças a sua disseminação no mercado e nas universidades brasileiras, o seu ótimo custo benefício e presença de ferramentas suficientes para a modelagem do sistema proposto. Assim como a maioria dos *softwares* de simulação, o Arena® visualiza o sistema a ser modelado como constituído de um conjunto de estações de trabalho que contém um ou mais recursos que prestam serviços a clientes (também chamados de entidades ou transações) que se movem através do sistema. O movimento pode ser feito pela própria entidade ou por transportadores (empilhadeiras, por exemplo). A entrada de dados no modelo pode ser realizada por meio de arquivos (MS Excel, por exemplo) contendo informações referentes as entidades que entram no sistema (informações como nome, prioridade, quantidade, tempo de chegada).

3 Materiais e Métodos

Nesta seção, os materiais e métodos empregados para a realização do trabalho são detalhados. Uma visão geral das etapas realizadas pode ser visualizada na Figura 1. Em seguida, uma apresentação da empresa estudada e o detalhamento de cada uma das etapas são apresentados.

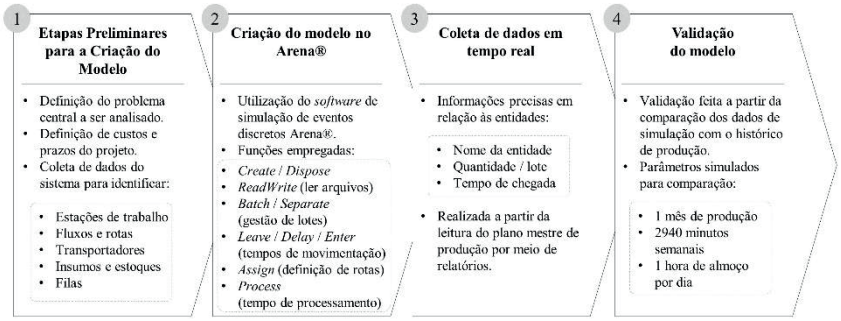

Fig. 1. Etapas da pesquisa.

3.1 A Indústria Moveleira em Estudo

A indústria moveleira em estudo está localizada no município de São Bento do Sul, interior do estado de Santa Catarina. É uma empresa média que conta com cerca de 120 funcionários. O produto principal são as camas e beliches, cujo o principal mercado é externo. Este trabalho tem como objetivo trazer melhorias para o setor de preparação da madeira, portanto será o único setor a ser analisado.

O setor de preparação é composto por: uma máquina de serra circular; uma máquina destopadeira manual; uma máquina otimizadora; uma máquina moldureira, associada a duas estações de trabalho que recebem diferentes tipos de produtos; uma prensa de alta frequência, associada a duas estações de trabalho que recebem os mesmos produtos; e por fim, uma máquina seccionadora. Cada máquina está equipada com um controlador de coleta de dados. Cada controlador apresenta dados importantes para o modelo, como: produtividade, parada e disponibilidade.

3.2 Etapas Preliminares para a Criação de um Modelo no Arena®

O projeto de simulação deve ter um objetivo claro, ter um tempo e custo aceitável de desenvolvimento, deve ser bem documentado e atingir o seu objetivo. Este objetivo primário deve ser claro para todos os envolvidos no projeto. Para isso, Prado (2010) define um projeto de simulação em duas etapas: Planejamento e Execução [14]. Nesse sentido, o planejamento se iniciou pela definição de um problema central a ser analisado, e pela definição de custos e prazos para a realização do projeto. Em seguida, foi realizada a coleta dos dados do sistema submetido à simulação. Essa coleta tem como objetivo a criação de um desenho que explicite o *layout*, permitindo a identificação de: equipamentos e estações de trabalho, rotas e fluxos de materiais, transportadores de materiais, insumos e estoques ao longo do processo produtivo, e também filas de entrada e saída das estações de trabalho. Ademais, a coleta dos dados é importante para o levantamento de anomalias no sistema, além do levantamento dos tempos de processamentos e das capacidades das filas e dos estoques.

3.3 Criação do Modelo no Arena®

Após a etapa preliminar de planejamento, a execução da modelagem foi realizada no *software* Arena®, a partir do emprego de algumas funções. A função *Create* foi utilizada para definir a cadência de entrada de novas peças no sistema, enquanto a função *dispose* foi utilizada para representar a saída de produtos do sistema. A função *ReadWrite* foi empregada para ler arquivos de texto, planilhas do *MS Excel* e planilhas do *MS Access*. As funções *Batch* e *Separate* foram utilizadas, respectivamente, para unir peças em lotes e separar peças de lotes. No âmbito das movimentações de peças entre máquinas, quatro funções foram utilizadas: a função *Delay* foi empregada para definir um tempo para a movimentação de uma peça, a função *Assign* foi usada para definir a rota que uma peça deve seguir, a função *Leave* foi utilizada para definir um período de tempo para que ocorra a saída de uma peça de uma estação, e a função *Enter* foi utilizada para definir um período de tempo para que ocorra a entrada de uma peça em uma nova estação. Por fim, a função *Process* foi empregada para indicar o tempo de processamento de uma peça em uma máquina.

3.4 Coleta de dados em tempo real

Uma parte importante do modelo de simulação é ter acesso a informações precisas de como as entidades a serem analisadas se comportam na entrada do sistema. É vital que dados como nome da entidade, quantidade, lote, tempo de chegada sejam o mais precisos possível. Por outro lado, o modelo deve simular em tempo real os cenários em que a fábrica se encontra. Portanto, a coleta de dados diretamente do plano mestre de produção é uma opção adequada. Periodicamente são gerados relatórios em formato MS Excel, contendo todos os dados de entrada importantes. Esses relatórios foram utilizados para alimentar o modelo de simulação, gerando previsões em tempo real conforme a demanda.

3.5 Validação do modelo

A validação do modelo foi feita com base no histórico de produção. O modelo reproduziu um mês de funcionamento da fábrica (2940 minutos semanais com 1 hora de almoço por dia) com base em dados de entrada já conhecidos. Os dados de saída do modelo foram comparados à produção ocorrida neste mês estudado.

4 Resultados e Discussão

O primeiro passo tomado foi a definição da entidade que seria analisada. O metro linear foi a melhor unidade de medida encontrada, que podia ser medida na vida real e aplicada no Arena®. Seguindo para a coleta de dados, foi desenvolvido um desenho do *layout* do setor de preparação. O desenho, que pode ser observado na Figura 2, contém as estações de trabalho, estoques e suas disposições no chão de fábrica.

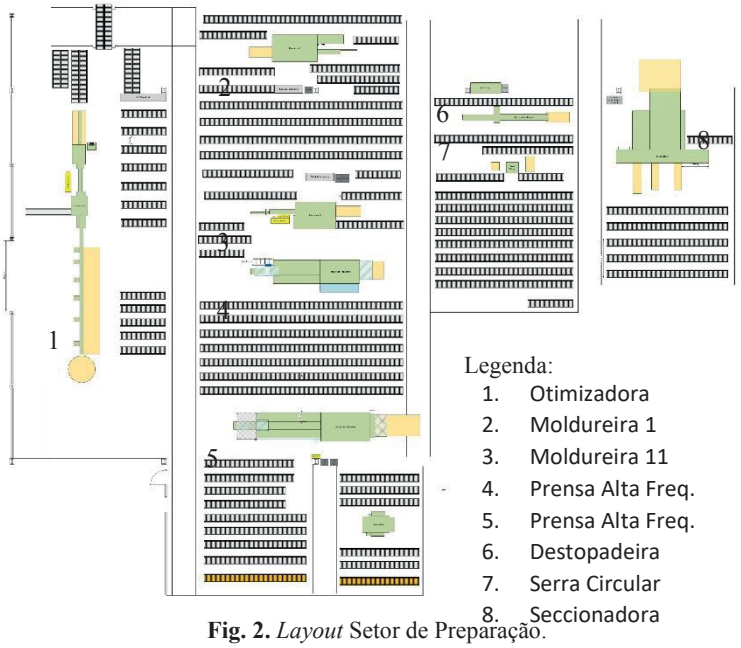

Fig. 2. *Layout* Setor de Preparação.

Em seguida, foi desenvolvido um fluxograma dos processos, apresentado na Figura 3. No fluxograma estão explícitas todas as rotas possíveis e seus destinos.

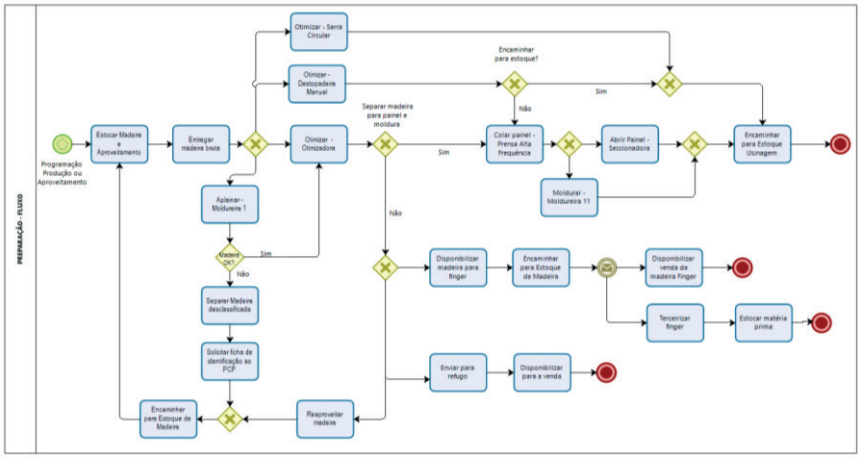

Fig. 3. Fluxograma de processos.

Devido a quantidade de produtos distintos que entram simultaneamente no sistema, foi necessária a separação das rotas. Ao todo foram identificadas 15 rotas. Cada rota representa uma família de produtos. A separação em rotas além de representar de maneira mais fiel a realidade, também torna possível um melhor controle de cada família

de produtos. Com essa separação também se torna possível uma melhor coleta de dados como tempo de um produto no sistema, valor agregado a esse produto. Podendo ao final do trabalho ser definido quais produtos devem ter prioridade no setor.

Tabela 1. Principais Rotas Identificadas.

Rotas Identificadas no setor de Preparação							
1	Estoque	Serra Circular	Estoque Usinagem				
2	Estoque	Destopadeira	Estoque Usinagem				
3	Estoque	Destopadeira	Prensa Alta Freq	Seccionadora	Estoque Usinagem		
4	Estoque	Destopadeira	Prensa Alta Freq	Seccionadora	Moldureira 11	Estoque Usinagem	
5	Estoque	Destopadeira	Prensa Alta Freq	Moldureira 11	Estoque Usinagem		
6	Estoque	Otimizadora	Prensa Alta Freq	Seccionadora	Estoque Usinagem		
7	Estoque	Otimizadora	Prensa Alta Freq	Seccionadora	Moldureira 11	Estoque Usinagem	
8	Estoque	Otimizadora	Prensa Alta Freq	Moldureira 11	Estoque Usinagem		
9	Estoque	Otimizadora	Moldureira 11	Estoque Usinagem			
10	Estoque	Otimizadora	Estoque Finger				
11	Estoque	Moldureira 1	Otimizadora	Prensa Alta Freq	Seccionadora	Estoque Usinagem	
12	Estoque	Moldureira 1	Otimizadora	Prensa Alta Freq	Seccionadora	Moldureira 11	Estoque Usinagem
13	Estoque	Moldureira 1	Otimizadora	Prensa Alta Freq	Moldureira 11	Estoque Usinagem	
14	Estoque	Moldureira 1	Otimizadora	Moldureira 11	Estoque Usinagem		
15	Estoque	Moldureira 1	Otimizadora	Estoque Finger			

Por fim, foi desenvolvido o modelo no Arena®, apresentado na Figura 4. Na figura, os módulos da esquerda representam as entradas do sistema. Como são analisados 15 produtos diferentes, foram criadas 15 rotas distintas. Os módulos utilizados foram:

- Módulos "*Create*". Cada módulo "*Create*" recebe os dados de entrada de cada produto no sistema (identificados como Estoque de Madeira Rota);
- O módulo "*ReadWrite*" permite que o modelo faça a leitura do plano mestre de produção;
- O módulo "*Separate*", associado ao módulo "*ReadWrite*", tem a função de coletar a sequência de valores lidos no módulo "*ReadWrite*";
- O módulo "*Delay*" (identificado como Logística interna de entrega de madeira ...) atribui um valor de tempo entre a saída de madeira do estoque inicial e a chegada em suas respectivas estações de trabalho;
- O módulo "*Assign*" tem a função de definir quais estações de trabalho (rotas) cada produto irá seguir;
- O setor de preparação faz o planejamento por meio de lotes, portanto, por meio do módulo "*Batch*", será possível unir o metro linear de madeira em um único lote para a sua movimentação.
- O módulo "*Leave*" permite a conexão entre os módulos acima citados e os módulos referentes as estações de trabalho.

Os módulos do meio representam as estações de trabalho, para cada uma foram adicionados os seguintes módulos:

- Módulo "*Enter*", adiciona um valor de tempo para a entrada do lote na estação de trabalho;
- Módulo "*Separate*", separa os produtos unidos com o módulo "*Batch*", ou seja, separa o lote de madeira em valores de metro linear;

- Módulo "*Process*" (identificado pelas máquinas) representa cada processo produtivo propriamente dito. Este módulo irá receber os tempos de processamento de cada máquina, coletados pelo controlador;
- Módulo "*Batch*", associado com o "*Process*", permite a união dos metros lineares em um lote;
- Módulo "*Leave*" adiciona um valor de tempo para a saída do lote da estação de trabalho;
- Os módulos "*Decide*", presentes após a otimizadora e a moldureira 11, separam o percentual de refugo e madeira de reutilização que saem dos respectivos processos.

Por fim, os módulos mais a direita representam as saídas do sistema. Neles foram adicionados os seguintes módulos:

- Módulo "*Enter*", representa o tempo de saída dos lotes de suas estações de trabalho até o estoque destino;
- Módulo "*Separate*", separa os lotes em metro linear;
- Módulo "*Dispose*" (identificados como Estoque Usinagem, Estoque Finger, Estoque Refugo, Estoque de Madeira), representa cada uma das saídas do sistema.

Além disso, foi definido que o modelo deverá simular um mês de produção. Por meio do módulo "*Schedule*", presente na definição de parâmetros do modelo, foi definido os horários em que cada estação de trabalho está disponível (de segunda-feira à quinta-feira das 07:00 às 17:00 e sexta-feira das 07:00 às 16:00, com pausa, todos os dias, das 12:00 às 13:00, para o almoço).

Para uma maior precisão do modelo, também são levantadas informações como: prioridade das rotas, percentual de refugo, falhas e manutenção.

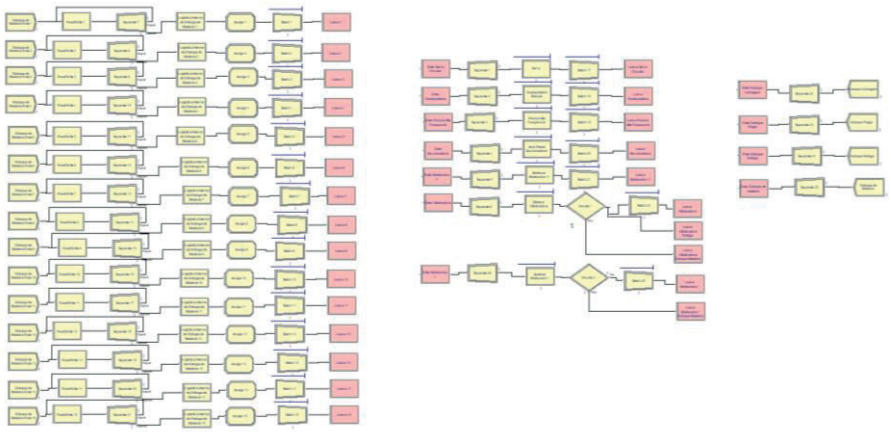

Fig. 4. Modelo desenvolvido no Arena®.

5 Conclusão

Para que o modelo de simulação seja funcional é necessário que todos os processos que ocorrem no ambiente de estudo sejam bem definidos, os tempos coletados de cada processo sejam precisos, os dados de entrada do sistema sejam os mais próximos do mundo real. Por meio da metodologia utilizada neste trabalho espera-se que o modelo tenha um alto índice de similaridade com a realidade. Após a validação do modelo, será possível identificar os seguintes dados:

- Quantidade total de metros lineares produzidos;
- Porcentagem da produção destinada para os diferentes estoques de saída;
- Quais produtos possuem maior valor agregado;
- Quais rotas possuem gargalos;
- Quais estações de trabalho estão sobrecarregadas;
- Qual a produtividade real de cada máquina.

Em seguida, por meio do relatório gerado pelo *software*, será possível identificar quais dados estão fora dos parâmetros ideais. Propostas de mudanças podem ser estudadas e aplicadas no modelo para que esses índices sejam atingidos. Dentre as possíveis mudanças:

- Mudança de *layout* atual;
- Compra de novas máquinas;
- Manutenção ou adaptação das máquinas atuais;
- Adaptação no transporte das peças.

Espera-se que após todo o processo, o modelo de simulação possa dar subsídios para a tomada de decisão da empresa. Vale ressaltar que os dados de entrada registrados no plano mestre de produção devem ser os mais precisos possíveis.

Do ponto de vista de oportunidades para trabalhos futuros, uma das possíveis propostas de melhoria para o modelo seria a adoção de um sistema automatizado que faça o registro de entrada das peças no sistema. Nesse sentido, o modelo de simulação pode incrementar suas capacidades de reconfiguração em tempo real, para garantir uma correspondência atualizada de seus parâmetros com as condições vigentes do sistema produtivo. A adição de tais capacidades aproximam o modelo das arquiteturas tecnológicas propostas no contexto da manufatura digital.

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A Multiple-Criteria Directional Measure for Resource Management in Hospitalizations

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Abstract. The recent pandemic crisis has highlighted the importance of efficiency-oriented strategies to prevent the collapse of health systems under limited resources over the world. This assessment combines the advances in the outranking Multicriteria Decision Aid to the frontier estimations of Data Envelopment Analysis to support resource management in hospitals during the pandemic. The methodology involves determining an optimal direction for input contraction using the PROMETHEE method based on health experts' value judgments to estimate hospitals' production capacity through linear programming. The assessment aims at providing an avenue for local administrations' strategic planning.

Keywords: Data Envelopment Analysis, Directional Distance Functions, Multicriteria Decision Analysis, Resource Allocation, Hospitals, Covid-19, Brazil.

1 Introduction

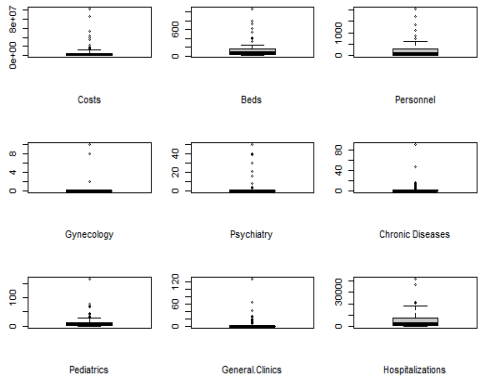
The recent pneumonia outbreak evidenced critical limitations in health systems around the world. Because several patients needed intensive care simultaneously, hospitals and other health support administrations with limited resources were unable to meet all the demand for health care services. As a result, health systems in many countries and regions collapsed due to the unavailability of beds, ventilators, personal protective equipment (PPE), human and other technical resources for new hospitalizations [1], testifying the need for efficient hospital resource management and evacuation protocols to increase the response capacity during this crisis.

Data Envelopment Analysis (DEA) is widely recorded in efficiency studies of hospitals [2]. DEA uses the ratio between output and input variables to calculate the relative efficiency of production units in a given context. The DEA application in hospitals offers performance indicators favoring guidelines for reducing the operational cost of medical units through the efficient use of resources [3], [4], [5]. In this work, an extension of the Directional Distance Function (DDF) for the inclusion of multiple subjective directions based on outranking procedures developed by Nepomuceno, Daraio & Costa [6] is used to support resource management in hospitals during the COVID-19 pandemic.

This methodology's value is noticeable in our decision problem, which is estimating the feasible efficient production capacity for hospitals based on both technical parameters and subjective evaluation of health professionals. This assessment offers an optimized measure for how many resources (beds) each health service unit can spare and reallocate through best practices. The considered inputs are the number of assistants and technicians, nurses, hospital beds, and hospitalization costs. The produced output is admissions (hospitalizations). The decision criteria for defining the feasible direction are the severity, flexibility, complexity of needs, assistance utility, and potential for replacement in the ten most recurrent medical specialties (in the number of hospitalizations). The 88 most essential hospitals and health care units in Pernambuco were selected for this analysis.

2 Data and Methodology

Hospitalizations under an operational perspective can be comprehended as a production system composed of technical (beds, personnel, equipment) and financial (costs) inputs used to produce several hospital internments (admissions or hospitalizations) with a final objective of providing sufficient care for a patient recovery[7]. In the directional efficiency assessment for hospitalization management, the number of beds for some recurrent and particular specialties was considered the analysis's inputs, having hospitalizations as the output. The total cost (investment) in hospitalizations for each health service unit was included as an additional input for controlling the scale and size of units. Another assessment (for comparison purposes) considered the costs, beds and staff (assistants and technicians) as the production inputs. Fig. 1 illustrates in boxplots a summary of descriptive statistics (range, mean, median, quartile, intervals, and outliers) for the considered variables.



Data corresponds to 88 public and private health service units in Pernambuco, Brazil. Some hospitals do not serve all types of specialties considered in this assessment. We used the costs of hospitalizations as a control input for the size and scale of units. Fig. 1 reports only the final considered specialties after outranking directions for the efficiency analysis and support reallocating beds and associated resources.

Fig. 1. Boxplots for Inputs and Output Data.

Directional Distance Functions Chambers et al. (1998) and Färe and Grosskopf (2004), Nepomuceno et al. (2020) are a flexible non-parametric alternative for meas-

uring the technical production capacity of health units generalizing the radial projection of traditional DEA methodologies. The efficiency is assessed by choosing a feasible direction $g = \mathrm{g}_{(x,y)} \geq 0$ where the resources (inputs) must be contracted and/or the outputs expanded in order to attain the efficient frontier. The inclusion of subjective judgments over input/outputs configurations in the definition of an objective efficiency measure is an interesting perspective when there is a clear preference for reducing (and reallocating) some specific inputs compared to others.

In the case of this assessment, the choice for the most appropriate resource contraction (and reallocation) was based on a multiple criteria evaluation of specialties that could contribute more significantly to minimizing the impact of the current pandemic. The PROMETHEE II [8][9] was used to defining directions for prioritizing the medical specialties where reallocations of beds and associated resources can be made. Formally, the directional efficiency model takes the following statement:

$$\mathrm{D}_t\,(\mathrm{x},\mathrm{y},\mathrm{gx},\mathrm{gy}) = max\ \beta$$

$$s.t. \quad \sum_{j=1}^{n} z_j\, y_{jr} \geq y_{or} + \beta g_{y_r} \quad r = 1,\ 2,\ \ldots,\ s$$

$$\sum_{j=1}^{n} z_j\, x_{ji} \leq x_{oi} - \beta g_{x_i} \quad i = 1,\ 2,\ \ldots,\ m$$

$$\sum_{j=1}^{n} z_j = 1,\ z_j \geq 0, \quad j = 1,\ 2,\ \ldots,\ n$$

Where $g_{x_i} = \frac{Q_i - \min(Q_i)}{\max(Q_i) - \min(Q_i)}$ is the rescaled input directional vector for the feasible contractions based on the PROMETHEE II complete preorder of alternatives given by the outranking net flow $Q_i = \sum_{i' \neq i}^{s} P(i,i') - \sum_{i' \neq i}^{s} P(\,i',i)$, which is the difference between the positive and negative outranking flows [9]. The rescaled input directional outranking vector defines an intensity of preference for input *i* to be reduced over input i' as a function of performance differences on decision criteria. The decision criteria considered in this elicitation process were the severity, flexibility, complexity of needs, assistance utility and potential for replacement on 10 crucial types of hospitalization: Gynecology, Psychiatry, Chronic Diseases, Pediatrics, General Clinics, Orthopedics/Traumatology, General Surgery, Obstetrics, Cardiology and ICU. Two health professionals responded to a 7–point Likert scale, and a public authority provided some valuable feedback for the consolidation of the analysis.

3 Results and Brief Discussion

The ranking of specialties in Table 1 reports the results of PROMETHEE outranking methodology [8]. The clinical specialties favorable to prioritization in evacuating beds and reallocating medical resources are Gynecology, Psychiatry, Chronicles Diseases,

Pediatrics and General Clinics. Figure 1 illustrates the overall production capacity with the efficiency frontier estimation by enveloping data under variable returns to scale technology. The frontier points represent the efficient hospitals working at full capacity (producing the maximum possible hospitalizations), which are benchmarks for best practices.

The remaining inefficient units (under the frontier) have about 4 thousand beds and more than 5 thousand human resources (mostly nurses) feasible to be reallocated in one year for new cases COVID-19. Managing these resources can only be effective by considering the formalization of new service protocols, postponing surgeries and decreasing the patients' length of stay in hospitals through best practices from their peers. Some of the hospitals with the best potential for reallocating beds and personnel are private institutions, which presents the challenge of planning and managing the medical resources by the local and state administrations.

Table 1. PROMETHEE Prioritization and Directions.

Position	Medical Specialty	Net Flow	Direction
1	Gynecology	0.74822	0.874110
2	Psychiatry	0.63933	0.819665
3	Chronic Diseases	0.25372	0.626860
4	Pediatrics	0.25372	0.626860
5	General Clinics	0.19372	0.596860
6	Orthopedics/Traumatology	-0.01888	0.490560
7	General surgery	-0.18039	0.409805
8	Obstetrics	-0.24854	0.375730
9	Cardiology	-0.79897	0.409805
10	ICU	-0.84194	0.375730

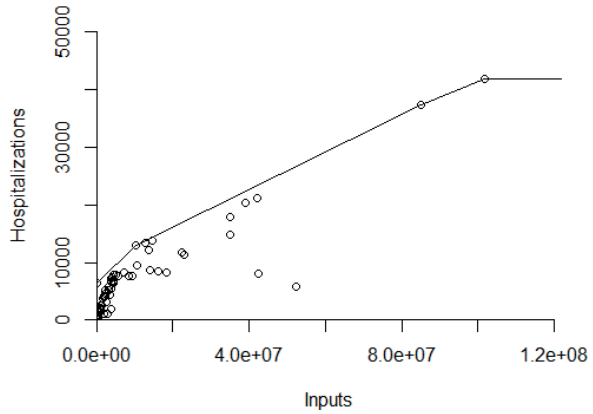


Fig. 2. Efficient Frontier of Hospitalizations.

Table 2 reports this analysis's main results regarding the allocation of beds and investments among specialties and health service units. The total number of beds that are feasible to be reduced (and reallocated) for other types of hospitalizations (e.g., COVID-19 cases) considering all 88 hospitals for each specialty is provided in the third column. Units (+) represent the number of inefficient health service units with the potential to provide beds or reallocate investments through best practices. Units (-) is the number of (efficient) hospitals working at full capacity considering each specialty, which cannot provide an additional resource for other units. The Gynecology specialty does not have sufficient data for coherent results because most units do not operate this specialty.

Table 2. Main Results.

Inputs	Directions	Reallocation of Inputs	Units (+)	Units (-)
Gynecology	0.874110	-	-	-
Psychiatry	0.819665	229	10	78
Chronic Diseases	0.626860	83.5	14	74
Pediatrics	0.626860	341.9	29	59
General Clinics	0.596860	264	9	79
Costs	0	140784626.14	12	76

Some interesting methodologies for resource allocation and investigating exogenous determinants of those reported metrics are provided by Nepomuceno et al. [10], [11]. The prospects of combining Multiple Criteria and DEA methodologies for assessments of this nature are not limited to this investigation's results. Additional considerations concerning the benchmarking of strategies for reducing the length of stay and service protocols are expected to focus on future investigations.

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Long-term evaluation of energy efficiency measures in transport, case study Paraguay

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Abstract. Although Paraguay is one of the world's largest exporters of electrical energy, its energy matrix depends mainly on biomass and hydrocarbons, the latter being imported. Based on this, this study evaluated efficiency measures for the main final use of hydrocarbons identified, namely long-distance land transport of cargo. Long-term diesel and electric rail transport scenarios were studied using an energy model developed in the Long-range Energy Alternatives Planning software and an energy, economic and environmental (related to emission savings) analysis was carried out. The results obtained show the great potential for economic, energy and environmental savings with the application of measures to replace end-use technologies and primary energy source, in the long term, in all branches of energy demand.

Keywords: Efficiency, diesel rail transport, electric rail transport, energy prospective, environmental analysis, cost-benefit analysis.

1 Introducción

Desde la década de 1970, Paraguay abastece su demanda eléctrica en base a aprovechamientos hídricos (inicialmente con la Central Hidroeléctrica Acaray), que fueron ganando participación con la construcción de dos grandes emprendimientos binacionales: Yacyretá con Argentina e Itaipú con Brasil. Actualmente, esta producción de electricidad llega a 6.199,4 miles de toneladas equivalentes de petróleo (tep) y está planificado aprovechar aún más el potencial hidroenergético del país, mediante proyectos como Aña Cuá, Itacora Itatí, Corpus y la adición de unidades generadoras en Yacyretá [1].

Sin embargo, a pesar de la abundancia de hidroelectricidad, la demanda energética del país es abastecida en base a biomasa e hidrocarburos, éste último es netamente importado, implicando un importante flujo de divisas al exterior [2]. Analizando los usos finales de hidrocarburos, se observa que el consumo principal se da en el transporte, dejando a este sector a entera dependencia de costos y disponibilidad de hidrocarburos en mercados internacionales. De los hidrocarburos importados, en el año 2014 la demanda de diésel representó 63.9% de importaciones de derivados de petróleo y un aumento del 14.6% respecto al año anterior [3]. Es importante destacar que para el transporte de cargas y pasajeros la principal fuente utilizada es el diésel.

Paraguay es predominantemente un país agropecuario y entre sus principales productos se pueden citar maíz, arroz, soja, carne vacuna, entre otros [4]. Según proyecciones del Plan Nacional de Logística (PNL) la producción llegaría a aproximadamente 157 millones de toneladas en el año 2030. Un porcentaje importante de esta producción es exportada, por lo que es transportada por vía terrestre [5] hasta los principales puertos fluviales del país, que se encuentran en las ciudades de Asunción (Central), Villeta (Central), Carmen del Paraná (Encarnación) y Pilar (Ñeembucu), como se observa en la Tabla 1 y Figura 1.

Table 1. Ubicación de los principales puertos

Ciudad	Departamento
Villeta, San Antonio, Villa Elisa, Zeballos Kue, M. R. Alonso, Ita Pyta Punta, Puerto Pabla	Central
San Juan del Paraná, Pacú Cuá, Hohenau, C.A. López,	Itapúa
Villa Hayes	Presidente Hayes
Villa del Rosario, Antequera	San Pedro
Concepción	Concepción
Pilar	Ñeembucú

Esta particularidad, de amplia disponibilidad de recursos hidroeléctricos y gran dependencia de hidrocarburos importados para un sector de la demanda, da cuenta de un potencial de eficiencia energética y ahorro económico en base al reemplazo de tecnologías de transporte de cargas. Este reemplazo/migración de tecnologías es planteado y estudiado en este trabajo, mediante un análisis energético, económico y ambiental a largo plazo, dentro de la matriz energética del Paraguay.

Este artículo está estructurado de la siguiente forma: en la Sección II, se presenta la metodología y la herramienta utilizada. En la sección III se exponen los resultados obtenidos. Finalmente, en la Sección IV, se concluye el trabajo.

2 Objetivo y Justificación

El principal objetivo de este estudio es proponer y evaluar medidas de eficiencia energética asignativa y sustitutiva de fuentes de energía para el transporte de carga Terrestre, buscando obtener un ahorro energético y económico, al mismo tiempo de emitir menos cantidad de gases de efecto invernadero (GEI), a largo plazo, aplicando medidas de eficiencia energética en el sector transporte de cargas, mediante sustitución de tecnologías de uso final para transporte y reemplazo de energía primaria para abastecer a estas nuevas tecnologías. Esto se traduce en realizar el transporte de cargas de larga distancia en base a trenes (eléctricos o diésel) para dejar de realizar este transporte mediante tracto camiones (diésel).

Según casación de datos de lugares y volumen de producción y exportación de bienes desde Paraguay, se puede identificar que gran parte de la importación de hidrocarburos

(diésel), es consumida en el sector transporte para acercar bienes producidos a lo largo del país, a puntos de exportación, ver Figura 1 y Figura 2. Cuando se mencionan producción de bienes, este trabajo se refiere a producción agropecuaria, específicamente granos.

3 Marco teórico y metodológico

Para realizar un análisis energético exhaustivo, se elaboró un modelo energético integral del Paraguay, donde se representó la estructura de energía primaria y secundaria, centros de transformación de energía y todos los sectores de demanda, con especial desagregación en el área de transporte, ya que el presente análisis se desarrolla en esta área. Este modelo es elaborado mediante la herramienta Long-range Energy Alternatives Planning (LEAP©) que permite simular escenarios de evolución de variables energéticas, alternativas de sustitución de fuentes energéticas y tecnologías de uso final, al mismo tiempo de realizar análisis ambiental de los escenarios propuestos [6].

3.1 Hipótesis consideradas

En este trabajo, la variable energética simulada, es la demanda del sector transporte de cargas de larga distancia, y las alternativas de reemplazo de tecnologías de uso final propuestas que son: tren diésel y tren eléctrico. Se planteó que estas tecnologías reemplazarán, en el largo plazo, un porcentaje del transporte de carga terrestre realizado mediante tracto camiones en el año base [7].

El modelo energético desarrollado en LEAP©, evoluciona desde un año base a un horizonte seleccionado, año 2030, tomando como fundamento de evolución ciertas variables conducentes, seleccionadas por el usuario.

Debido a la disponibilidad de datos energéticos desagregados para el año 2011, se seleccionó este año como año base para el presente estudio y se tomaron datos energéticos y desagregación del sistema energético paraguayo en base al balance de energía útil de la república del Paraguay del año 2011 (BEU) [8].

Además, en el desarrollo del modelo energético, se consideraron otras hipótesis constructivas explicadas a continuación.

Variables conducentes

Las variables conducentes de demanda, consideradas en este trabajo, que determinaron el comportamiento del modelo son: variables macroeconómicas y demográficas. En el modelo desarrollado se establecieron proyecciones del producto interno bruto (PIB) de los sectores de demanda, proyecciones valor agregado bruto del relacionadas al sector transporte (VAB) en estudio, proyecciones de crecimiento de la población, evolución de cantidad de hogares, proyecciones de producción de bienes y proyecciones de flota vehicular.

El desarrollo de este trabajo se centra en el sector transporte, con desagregación específica en el transporte de cargas a larga distancia. Por ende, todas las ramas del modelo energético fueron modeladas en base a sus respectivas variables conducentes sin

ninguna modificación en el largo plazo, al igual que no se consideró ninguna medida de reemplazo de tecnologías o fuentes energéticas en sectores distintos al de transporte.

Análisis de la Prospectiva Energética

El análisis prospectivo a largo plazo se realizó mediante la técnica de escenarios, donde se tiene como base un escenario business as usual o tendencial, donde no se contempló ningún tipo de modificación en la matriz energética. Luego, se plantearon dos escenarios alternativos, donde, en el primer escenario alternativo, el transporte de cargas se realizó mediante trenes a diésel, y en el segundo por medio de trenes eléctricos.

En este estudio prospectivo, se mantuvo la desagregación propuesta en el BEU y, además, se agregó una desagregación específica en el transporte de cargas a larga distancia, lo que posibilitó el análisis de las hipótesis planteadas.

4 Desarrollo del Estudio

Con base a la propuesta metodológica presentada, se consideraron tres escenarios de transporte descritos a continuación:

4.1 Primer Escenario: Escenario Tendencial o business a usual

En el escenario tendencial no se propuso ningún tipo medidas de eficiencia, sustitución de tecnologías o fuente energética. Este escenario representa las tendencias del sector energético si no se realizan cambios en la matriz energética. Ya que el modelo evoluciona la demanda en todos los sectores de consumo en base a las variables conducentes.

Además, analizando correlaciones dentro del sistema energético, se observa que, al aumentar la producción de bienes, aumenta la demanda de diésel para transportar estos bienes para su consumo y exportación, lo que al mismo tiempo implica el aumento del parque vehicular para este tipo de transporte.

En base al comportamiento de este escenario tendencial, se obtuvieron datos que fueron base para los siguientes escenarios propuestos. Entre los principales datos, se determinó el consumo específico de tracto camiones para transporte de cargas, varios puntos de origen (que se corresponden con puntos de producción de bienes) y destino de estas cargas (que se corresponden con puertos hídricos, para acceso a hidro vías para exportación de estos bienes). En base a esto y comprobando con datos de exportaciones de bienes [5], se determinó el peso de estos bienes exportados, un dato importante para los escenarios alternativos que propuestos a continuación.

En la Figura 1 se observan las rutas nacionales existentes, franja de dominio de ferrocarriles, hidro vías y puertos principales, luego, En la Figura 2 se observan las áreas de mayor producción de bienes en el país.

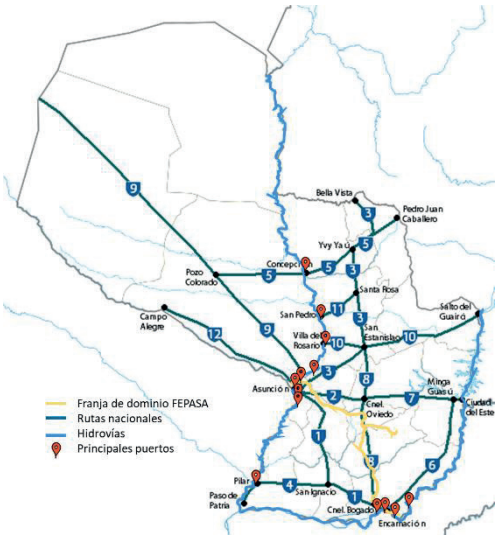

Fig. 1. Rutas nacionales, puertos e hidro vías principales.

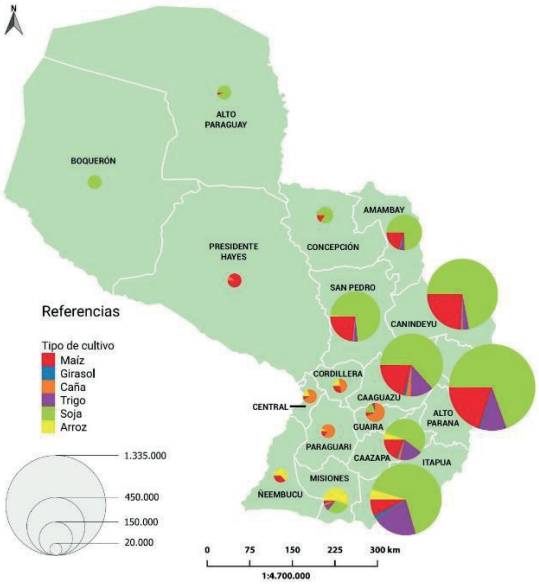

Fig. 2. Productos más exportados.[9]

4.2 Segundo Escenario: Escenario con tren diésel

En base a los datos obtenidos en el primer escenario, se propuso trayectos/tramos potenciales de transporte ferroviario movido a diésel para transporte de cargas que se

representaron en la Figura 3, donde se aprovecharon las franjas de dominio ya existentes para transporte (vial y ferroviario) que pasan por los puntos más productivos del país.

De estos tramos/trayectos propuestos, se resalta la ventaja de que se cuentan con instalaciones de acopio de productos, al igual que se utilizarían franjas de dominio existentes de FEPASA, evitando expropiaciones para nuevas franjas y se consideran los puntos de mayor producción del país. Según los trayectos trazados y en base a los puntos de producción afectados, se determinó que el 72% de la producción nacional es transportada mediante transporte ferroviario hasta los puntos de entrega.

El trayecto completo con los tramos que fueron considerados para transporte ferroviario, son explicados en detalle a continuación, al mismo tiempo de estar ilustrados en la Figura 3.

El tramo NORTE se considera desde la intersección entre la ruta 3 y la ruta 5 en la ciudad de Yby Yau. El tramo continúa siguiendo la dirección sur hasta la intersección entre la ruta 3 y la ruta 8, posteriormente recorriendo la ruta 8 hasta la ciudad de Villarrica. Desde allí llega a Paraguarí a través de la franja de dominio de FEPASA [10] finalizando en la ciudad de Villeta.

El tramo ESTE considera todo el recorrido de la ruta 7, continuando desde la ciudad de Coronel Oviedo por la ruta 8 hasta la ciudad de Villarrica, posteriormente siguiendo con el mismo trayecto que se consideró en el tramo Norte, culminando en Villeta.

El tramo SUR recorre la franja de dominio desde la ciudad de Encarnación hasta la ciudad de Paraguarí, continuando hasta Villeta, con el mismo tramo considerado en el tramo Norte entre las dos ciudades.

Los departamentos que afectan dichos tramos son: Concepción, San Pedro, Guaira, Caaguazú, Caazapá, Itapúa, Paraguarí, Alto Paraná, Central.

La producción en estos departamentos es de aproximadamente el 72% de toda la producción de bienes. En este trabajo, se consideró que el resto de la producción (28%) seguiría siendo transportada en tracto camiones, que anteriormente transportaba el 100% de la producción. Dicha sustitución se considera que entrará en vigencia en el año 2020.

Como puede observarse en la Figura 3, el punto de convergencia de todos los tramos propuestos es la ciudad de Villarrica, y el punto de llegada final es la ciudad de Villeta debido a que en la localidad se encuentran los puertos principales sobre el rio Paraguay, la hidro vía más importante para importación y exportación de bienes (punto de conexión con el transporte fluvial).

4.3 Tercer Escenario: Escenario con tren eléctrico

En el escenario Tren Eléctrico se tuvieron en cuenta las mismas consideraciones que en el segundo escenario con respecto al recorrido y porcentaje de bienes a transportar.

En este caso, el diésel se sustituye por electricidad. Al igual que el escenario de Tren Diésel, el Tren Eléctrico estaría sustituyendo a un sector de los Tracto Camiones, es decir, al 72% de la producción transportada. El año de entrada de dicho escenario es en el año 2020.

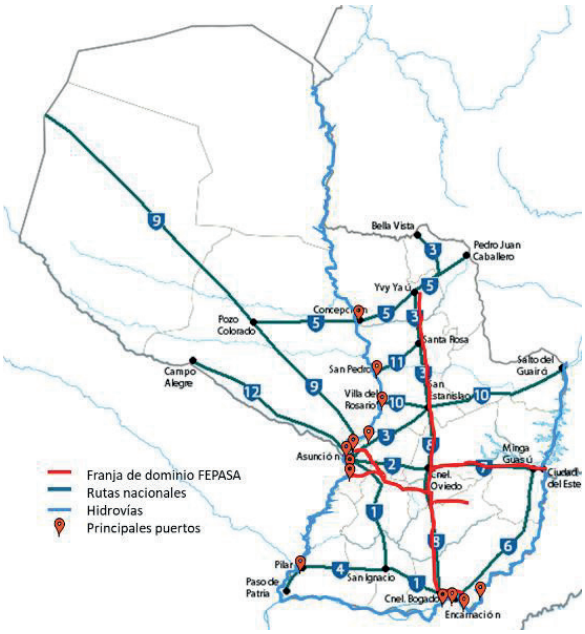

Fig. 3. Tramos y trayectos propuestos para transporte ferroviario.

5 Resultados

Para el cálculo de resultados, se tuvieron en cuenta consumos específicos de diésel y electricidad [11], y el nivel de demanda dependió del volumen y peso de los bienes que se consideran para transporte ferroviario.

En las tablas a continuación, se presentan los resultados de cada escenario calculado. En la Tabla 1, que corresponde al escenario tendencial, se presenta el consumo de las demandas en miles de toneladas equivalentes de petróleo (mtep), el aumento de la es determinado por las variables conducentes del modelo.

Table 2. Consumo del escenario tendencial para todas las ramas de demanda y todas las fuentes energéticas. Valores en miles toneladas equivalentes de petróleo.

Escenario Tendencial				
Rama	Año			
	2015	2020	2025	2030
INDUSTRIA	7.026	15.606	25.217	35.860
PUBLICO Y OT	584	1.195	1.826	2.477
COMERCIAL	2.918	5.821	8.699	11.546
RESIDENCIAL	4.437	9.216	14.312	19.700
TRANSPORTE	8.253	19.461	35.126	56.287
Total	23.219	51.299	85.181	125.871

En la Tabla 2 y Tabla 3 se presentan los resultados de demanda del escenario tren diésel y tren eléctrico respectivamente. Como se mencionó anteriormente, no se realizaron modificaciones de eficiencia o reemplazo de tecnologías ni fuentes energéticas,

por lo que los valores correspondientes a consumos para todas las ramas diferentes de transporte, son los mismos.

Table 3. Consumo del escenario tren diésel para todas las ramas de demanda y todas las fuentes energéticas. Valores en miles de toneladas equivalentes de petróleo.

Escenario Tren diesel				
Rama	Año			
	2015	2020	2025	2030
INDUSTRIA	7.026	15.606	25.217	35.860
PUBLICO Y OT	584	1.195	1.826	2.477
COMERCIAL	2.918	5.821	8.699	11.546
RESIDENCIAL	4.437	9.216	14.312	19.700
TRANSPORTE	7.546	14.882	22.917	31.304
Total	22.512	46.720	72.972	100.888

Table 4. Consumo del escenario tren eléctrico para todas las ramas de demanda y todas las fuentes energéticas. Valores en miles de toneladas equivalentes de petróleo.

Escenario Tren eléctrico				
Rama	Año			
	2015	2020	2025	2030
INDUSTRIA	7.026	15.606	25.217	35.860
PUBLICO Y OT	584	1.195	1.826	2.477
COMERCIAL	2.918	5.821	8.699	11.546
RESIDENCIAL	4.437	9.216	14.312	19.700
TRANSPORTE	7.546	14.882	22.458	30.235
Total	22.512	46.720	72.513	99.819

Como se puede observar en las tablas presentadas, la rama de transporte presentó una disminución considerable en el consumo para los escenarios alternativos propuestos. Para cuantificar este ahorro con cada escenario, se presentan los consumos porcentuales para cada escenario, pero puntualmente para la rama de transporte. En la Tabla 4 se puede apreciar que tanto el escenario de tren diésel como el escenario de tren eléctrico, presentan una disminución importante del consumo energético (ya sea diésel o electricidad) de entre 76% y 54%, tomando como base el escenario tendencial.

Table 5. Consumos porcentuales, en base al escenario tendencial, de escenarios alternativos para la rama de transporte.

Escenario	Año			
	2015	2020	2025	2030
Tendencial	100%	100%	100%	100%
Tren diesel	91%	76%	65%	56%
Tren eléctrico	91%	76%	64%	54%

6 Análisis económico

Para el análisis económico, se calculó el costo de oportunidad de cada alternativa en comparación con el escenario tendencial (no es un análisis de viabilidad financiera), sólo teniendo en cuenta las variables energéticas involucradas, mediante costos

incrementales acumulativos de cada escenario, y cada costo fue descontado a una tasa del 10% anual desde el año 2020.

Se tomaron datos históricos de costos de adquisición de fuentes energéticas. Ya que sólo se analizó el reemplazo de tracto camiones a tren diésel (misma fuente energética, cambio de tecnología de uso final) y de tracto camiones a tren eléctrico (diferentes fuentes energéticas y diferentes tecnologías de uso final), se tienen en cuenta los costos del diésel y de la electricidad.

Se tuvo en cuenta el valor actualizado neto del costo de las fuentes energéticas involucradas en los escenarios propuestos, ya sea que éstas dejan de importarse (diésel) o dejan de exportarse (electricidad). En este análisis económico no se consideró el costo de instalación de infraestructura necesaria, adquisición de nuevas tecnologías ni la operación y mantenimiento de estas nuevas tecnologías.

Para el escenario de tren diésel, se tomaron datos históricos de precios internacionales referenciales del diésel 2011 a 2018 [12] y se extrapolaron al 2030 (se estiman valores futuros en base a series de datos históricos). Para datos de electricidad, se tomaron datos de compra de energía eléctrica de Itaipú de 43 USD/MWh, este valor se mantuvo constante durante todo el periodo de análisis.

En la Tabla 5 se presentan el análisis de costo beneficio, con respecto al escenario tendencial. Se evidencia una diferencia considerable de costo de oportunidad de ambos escenarios, para el escenario de tren eléctrico el beneficio está relacionado a dejar de importar diésel y para el escenario de tren diésel el beneficio representa la disminución del consumo de diésel y por ende menor importación. Además, en el escenario de tren eléctrico se tiene una consecuencia en la disminución de la exportación de energía eléctrica.

Si además se valoriza la disminución de gases de efecto invernadero (GEI), se puede aumentar el costo de oportunidad del escenario de tren eléctrico. Si bien existe un mercado de bonos de carbono, estos precios aún son insuficientes para incentivar a una economía de descarbonización, de igual forma, se tomaron valores de costo tonelada de CO_2 equivalente en mercados de bonos de carbono, valores tomados del LEAP©, para presentar el valor actualizado neto, expresado en dólares por toneladas de CO_2 equivalente, de las emisiones que se dejaron de emitir, última línea de la Tabla 6.

Table 6. Análisis costo beneficio de escenarios alternativos en comparación con el escenario tendencial. Valor actualizado neto al año 2030, en millones de dólares.

Sector	TREN ELECTRICO	TREN DIESEL
Imports	3.157	2.854
Exports	-58	-
Total Net Present Value	166.640	217.678
Cost of Avoided GHGs (USD/Tonne CO2e)	2.193	3.078

7 Impacto ambiental

7.1 Emisión de gases de gases de efecto invernadero (GEI).

Para realizar el análisis ambiental, se comparan los ahorros en emisión de GEI de los escenarios alternativos en comparación con el escenario tendencial. Estos datos están comparados al año 2030.

En el año horizonte del escenario tendencial, se tiene un nivel de emisión de 160 millones de toneladas de CO_2 equivalente, mientras que en los escenarios alternativos se tienen valores muy inferiores, en el escenario de tren diésel, 89 millones de toneladas de CO_2 equivalente por la disminución en el consumo de diésel, y en el escenario de tren eléctrico se evidenció una disminución en comparación al escenario tendencial, de 84 millones de toneladas de CO_2 equivalente.

Esta situación se debe a que, si bien hay un reemplazo de fuente primaria de energía, de diésel a electricidad, el consumo de diésel en el escenario de tren diésel es muy reducido, lo que lleva a que la diferencia de las emisiones sea pequeña en comparación con las emisiones totales del sistema energético, datos que pueden observarse en la Tabla 6.

Table 7. Ahorro de emisiones de GEI de escenarios alternativos en comparación con escenario tendencial. Valores en millones de toneladas de CO_2 equivalentes.

Sector	TREN ELECTRICO	TREN DIESEL	TENDENCIAL
GHG emission (Mill Tonnes CO2e)	84,31	89,59	160,30
GHG Savings (Mill Tonnes CO2e)	75,99	70,71	-

Como se puede apreciar los escenarios que presentan una disminución considerable en la emisión de gases de efecto invernadero de ambos escenarios propuestos, con respecto al tendencial.

8 Discusiones

En base a todos los resultados y análisis realizados, se evidencia el potencial de ahorro energético, económico y social en la rama de transporte, para el transporte de cargas.

Sin embargo, el consumo de hidrocarburos sigue siendo elevado, teniendo en cuenta la disponibilidad de hidro electricidad disponible para uso interno del país. Lo que denota que aún existe un potencial importante para ahorros energéticos, económicos y ambientales.

En este trabajo no se tuvieron en cuenta costos de inversión, instalación, operación y mantenimiento de nuevas tecnologías, pero, este análisis podría explorarse en trabajos futuros, en conjunto con la cuantificación de disminución de tiempos logísticos para transporte de carga y la consideración de la posible reconfiguración de transporte de carga aérea con las facilidades ofrecidas por el transporte ferroviario.

9 Conclusiones

Del análisis energético del Paraguay, se observó que es un país con amplia disponibilidad hidro eléctrica, pero gran dependencia de hidrocarburos y biomasas para fines energéticos, lo que llevó a proponer medidas de reemplazo de fuentes energéticas y tecnologías de uso final en el sector transporte.

Con este trabajo se demostró que existe una oportunidad importante de ahorro económico, energético y ambiental al implementar opciones de transporte ferroviario de cargas, sin embargo, estos ahorros pueden ser aún mayores si se estudian medidas de reemplazo de fuentes energéticas y tecnologías de uso final en otros sectores de la demanda, especialmente los dependientes de hidrocarburos y biomasa.

Si bien el análisis económico realizado es de costo de oportunidad, se puede considerar, muy a grandes rasgos, la influencia en la matriz/balance económico del país los beneficios económicos de ambos escenarios alternativos propuestos, y se puede concluir que tendrán un impacto positivo al disminuir la dependencia de importaciones para el sector energético.

Aunque el alcance de este trabajo no cubre un análisis de transporte por hidro vías, transporte de cargas aéreo, ni transporte de pasajeros en corta y larga distancia, los resultados de este trabajo son un punto inicial que dan cuenta de los beneficios económicos para el uso de la hidro electricidad disponible para consumo interno. Si bien, para realizar un análisis integral se deben considerar costos de inversión, operación y mantenimiento de nuevas tecnologías, los ahorros ambientales y energéticos justificarían estas inversiones, ya que Paraguay está adherido al acuerdo Paris y precisa de acciones concretas en el mediano y largo plazo para el cumplimiento de este acuerdo.

Además, es importante mencionar que la metodología aplicada en el análisis realizado, puede replicarse para analizar otras ramas de demanda, otros países, regiones y proyectos de integración de varios países.

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Método Multicriterio Grupal para Decisiones Rutinarias

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Resumen. El artículo analiza el problema de tomar decisiones con enfoque multicriterio, en grupos cuyos miembros comparten objetivos y decisiones de rutina. Estos procesos ofrecen ventajas: aprendizaje colaborativo y compromiso con las acciones acordadas. Como contrapartida, las decisiones grupales requieren tiempo y pueden ser afectadas por la presión grupal o por perturbaciones en la información disponible (imprecisión, incertidumbre o carencia de algunos datos). Se estructura un problema frecuente en una organización, con una cantidad finita de criterios y se adoptan para cada uno, categorías que permiten clasificar a las alternativas analizadas. Las prioridades de los criterios y las preferencias de las categorías, se representan mediante utilidades cardinales de tipo subjetivo. El método incluye dinámicas orientadas a reducir la presión de grupo, las perturbaciones y los tiempos de análisis. El documento analiza una aplicación al tratamiento de no conformidades, en un proceso productivo. En las conclusiones, se destaca que los participantes adoptaron la metodología y lograron consensuar las categorías. Además, valoraron que esta aproximación permite reducir los tiempos de análisis.

Palabras Claves: Toma de decisiones en grupo – Apoyo multicriterio a la decisión - Toma de decisiones de rutina – Evaluación por categorías

1. Introducción

La necesidad de tomar decisiones en grupo, es un requerimiento habitual en las organizaciones. Con frecuencia, la estructura del problema de decisión permite la aplicación de métodos de decisión multicriterio discreta, donde las preferencias y prioridades de los integrantes del equipo de trabajo, se expresan mediante utilidades de tipo cardinal.

En Luoma (2016), se postula que las situaciones de toma de decisiones pueden dividirse en dos clases: rutinarios (problemas recurrentes) y de acciones para la mejora. En situaciones rutinarias, el problema puede ser complejo y aplicar un procedimiento de toma de decisiones, puede convertirse en una tarea exigente.

Sin embargo, es importante buscar el mejor modo de sustentar esas actividades decisionales, porque cuando es posible reducir y controlar las perturbaciones que los afectan, estos procesos generan compromiso con las acciones decididas y empoderan

a los participantes (Brocklesby, 2016), (Montibeller y Winterfeldt, 2015), (Staggs SM., Bonito JA., Ervin JN., 2018).

Al respecto, este trabajo aplica un método de toma de decisiones en grupo, que estructura un problema frecuente de decisión con criterios subjetivos y un conjunto de clases, previamente definido y valorado que facilitan la evaluación dentro de cada criterio. Para establecer la valoración relativa de las categorías, las preferencias se representan mediante utilidades cardinales. Luego, se clasifican las alternativas consideradas en la estructura de criterios previamente definida.

2. Metodología propuesta

La propuesta tiene dos fases: la primera, permite estructurar el problema de decisión y estimar los parámetros del mismo, la segunda, consiste en aplicar en forma recurrente el modelo obtenido, cada vez que se repite la necesidad de adoptar un tipo de decisión rutinaria.

En la primera fase, se define el grupo de trabajo y se realizan entrevistas individuales y semi estructuradas, destinadas a identificar los criterios y las categorías a considerar para cada criterio. Una vez definidos y verbalizados los criterios y las categorías, para valorizarlos se utiliza un método para la toma de decisiones grupales conocido como Procesos de Decisión con Reducción de Variabilidad (Procesos DRV). De este modo, es posible asignar utilidades cardinales a los criterios y sus categorías (Zanazzi, 2016). Las fases generan un ciclo de aprendizaje grupal que se integra con diversas actividades (ver Fig. 1).

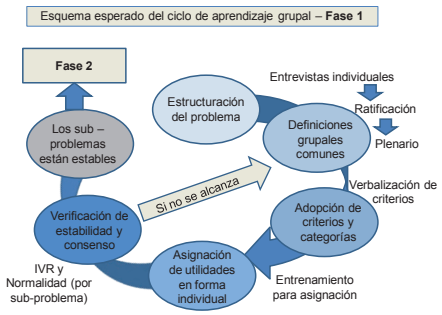

Fig. 1. Actividades desarrolladas en la fase 1(Fuente: elaboración propia).

La segunda fase consiste en la aplicación recurrente del modelo adoptado, cada vez que se repite el problema en la dinámica organizacional. En esa fase, el grupo de decisores solo debe clasificar cada alternativa en una categoría por criterio y determinar, mediante ponderación lineal, el valor global de la misma.

3. Resultados y discusión

El método se aplicó en un proceso de producción de bienes, con la finalidad de establecer prioridades para el tratamiento de no conformidades (fallas en el producto). Participaron dieciséis personas en el ejercicio inicial. Los criterios adoptados fueron: Urgencia; Complejidad; Costo Promedio de Resolución; Gravedad y Ocurrencia. Para cada criterio se utilizaron categorías. La siguiente Tabla 1 resume los criterios y las categorías obtenidas.

Tabla 1. Tabla con criterios y categorías.

CRITERIOS	CATEGORIAS
COSTO PROMEDIO DE RESOLUCIÓN (CPR): Se aplica el valor promedio de resolución de la IMNC resultante de la cantidad de horas de mano de obra directa e indirecta y el costo de materiales.	Bajo
	Medio
	Alto
OCURRENCIA: Frecuencia de la aparición de las novedades	Muy frecuente
	Frecuente
	Poco frecuente
COMPLEJIDAD: Está asociado al tiempo de resolución de la novedad. Se tiene en cuenta el análisis de la no conformidad y el tiempo de ejecución del retrabajo.	Alta
	Media
	Baja
URGENCIA: Se valora como la proximidad de ejecución de las tareas siguientes afectadas por alguna o varias novedades.	Muy Urgente
	Poco Urgente
	Nada Urgente
GRAVEDAD: Evalúa el impacto que la novedad produce. Para esto se define si el producto afecta o no la seguridad en vuelo, conforme requisitos de la norma.	Afecta
	No afecta

En la estimación de parámetros mediante Procesos DRV, fueron necesarios tres ciclos de análisis hasta lograr estabilidad y consenso, en las ponderaciones de los criterios. En cambio, para las categorías para cada criterio, demandó un sólo ciclo de intercambio. La síntesis de las ponderaciones puede verse en la Tabla 2.

Tabla 2. Resultados estimación de parámetros.

CPR			Ocurrencia			Complejidad			Urgencia			Gravedad		
Parámetros	*0,343*	*0,056*	Parámetros	*0,314*	*0,041*	Parámetros	*0,195*	*0,053*	Parámetros	*0,079*	*0,017*	Parámetros	*0,069*	*0,030*
Categorías	*Prom*	*Desv*	Categorías	*Prom*	*Desv*	Categorías	*Prom*	*Desv*	Categorías	*Prom*	*Desv*	Categorías	*Prom*	*Desv*
Alto	0,468	0,096	Alta	0,438	0,067	Alta	0,447	0,060	Alta	0,435	0,069	Afecta	0,752	0,026
Medio	0,353	0,082	Media	0,347	0,061	Media	0,367	0,051	Media	0,343	0,066	No afecta	0,248	0,026
Bajo	0,179	0,071	Baja	0,215	0,061	Baja	0,187	0,045	Baja	0,222	0,045			

Para ejercitar la mecánica de la segunda fase, en su primera aplicación, los participantes clasificaron cinco informes de no conformidad (IMNC). Se toma una

alternativa y se la clasifica en las categorías adoptadas para cada uno de los criterios conforme Tabla 3.

Tabla 3. Clasificación de alternativas.

Despcripción	CPR	Ocurrencia	Complejidad	Urgencia	Gravedad
IMNC 1	Bajo	Alta	Media	Media	Afecta
IMNC 2	Alto	Baja	Alta	Baja	Afecta
IMNC 3	Medio	Media	Baja	Alta	No afecta
IMNC 4	Alto	Alta	Alta	Alta	Afecta
IMNC 5	Bajo	Baja	Baja	Baja	No afecta

Por último, se calculan los valores estimados de media y desvío. Finalmente, se obtienen las valoraciones globales por ponderación lineal.

4. Conclusiones

Los procesos de toma de decisiones rutinarios configuran una actividad habitual y compleja en las organizaciones. La instancia grupal permite la construcción colaborativa de conocimiento y sus desventajas pueden modelarse con Procesos DRV.

El grupo demostró una participación activa y sus integrantes adoptaron sin inconvenientes la metodología. Lograron acordar categorías y percibir mejoras en los tiempos de análisis. El modelo puede ser utilizado cada vez que sea necesario, sin tener que realizar nuevas comparaciones. La estructura de criterios y categorías ponderados se mantiene para priorizar las demás no conformidades. Esta oportunidad brinda flexibilidad y rapidez para su uso.

Para futuras investigaciones se identifica la posibilidad de trabajar con otros criterios y más cantidad de categorías, así como la utilización de indicadores de gestión o priorizaciones previas, realizadas con otras herramientas.

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Increasing Confidence in Industry 4.0 through new Software Verification and Validation Techniques

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Abstract. Industry 4.0, the fourth phase of Manufacturing and IT is one of the pioneering research areas, especially in the last half of a decade, with a profound impact on economic and societal progress. Software has become a transversal and foundational element of this new industrial revolution; so the quality of the software has a direct impact on the quality of the processes of digital manufacturing, user experience, and product quality. This new era requires new methodologies and techniques to verify and validate the foundations of Industry 4.0. In this paper, we present a new framework for testing Object-Oriented Software developed using Java. It was designed and implemented to detect failures in the sequence of calls that objects make without the need to modify the source code. This framework is open source and is freely available.

Keywords: Verification and Validation, Testing, Message Sequence Specification, Aspect-Oriented Programming, Software

1 Introduction

Software quality has become one of the most important factors in determining the success of products or companies in the era of Industry 4.0. As stated by Oztemel et. al [11] "...the superior quality of the manufacturing industry strictly depends on its high quality applied production technology..." and "...there are now companies having the largest part of business in their sector with only running a software...". Lee et. al [8] also highlighted the key role of software in this new industry "The Fourth Industrial Revolution is ubiquitous and will increasingly transform and reshape operations/production, supply-chain, management, and governance as well as products and services. Whatever could be codified of the organizational life will be put into codes and software and embedded into cybernetics systems that will replace human work activities". Yang [9], as well, described that "Industry 4.0 has two key factors: integration and interoperability. Integrated with malicious applications and software systems, Industry 4.0

will achieve seamless operations across organizational boundaries and will realize networked organizations". To a great extent, the success of Industry 4.0 rests on the quality of the software, which has the responsability to ensure that it is error-free.

This new context forces us to design and develop new methodologies and tools to find and correct errors in the software. Various methodologies, techniques and frameworks have been developed to achieve a high-quality software product. Each development and adaptation was for specific areas or features of the software under review with a focus on particular types of errors. In 1994, Kirani and Tsai [3] presented a technique called Message Sequence Specification (MSS) that, in the context of an Object-Oriented program, describes the correct order in which the methods of a class should be invoked. This methodology has never been implemented as a framework for software verification and validation until our development.

In this paper, we present TAPIR, a framework designed to detect failures in the sequence of method calls. It relies on the concept of Message Sequence Specification and implements it as a dynamic testing tool. The implementation was done using Aspect-Oriented Programming (AOP) [4] and, therefore, it can be used in any Java project without the need to modify the implementation of the project. This work continues the one carried out in [6] and presents the latest updates. This new version can test multiple instances of multiples classes in the system. The rest of the paper is structured as follows. Section 2 provides background information about the MSS. In Section 3 we detail how MSS has been used so far. Then, we present our work in Section 4 with all its features. We later introduce two usage examples of the framework. Finally, we conclude with a brief discussion on the limitations and advantages of our approach and the future work.

2 Message Sequence Specification

In 1994, Kirani and Tsai [3] presented a technique called Message Sequence Specification (MSS) that, in the context of an Object-Oriented program, describes the correct order in which the methods of a class should be invoked by its clients. The MSS associated with an object specifies all sequences of messages that the object can receive while still providing correct behavior. Their strategy used regular expressions to model the constraints over the correct order of the method invocation, i.e. the regular expression is the test model. Method names were used as the alphabet of the expression which was then used to statically verify the program's implementation for improper method sequences. A runtime verification system identifies incorrect method invocations by checking for sequence consistency with respect to the sequencing constraints. According to Kirani and Tsai's specification, if a class C has a method M_1, this is noted as C_{M_1}. Sequence relationships between two methods were classified into three categories, sequential, optional, and repeated. If the method M_1 of C should be invoked before the method M_2 of the same class, then this relationship is sequential and

is represented as

$$C_{M_1} \bullet C_{M_2} \tag{1}$$

If only one of the methods M_1 and M_2 can be invoked, then this relationship is optional and is represented as

$$C_{M_1} | C_{M_2} \tag{2}$$

Finally, if the method M_1 can be invoked many times in a row then this is a repeated relationship and is represented as

$$(C_{M_1})^* \tag{3}$$

For example, if a class X has three methods called *create*, *process*, and *close*, a possible sequencing constraint based on MSS could look like

$$X_{create} \bullet (X_{process})^* \bullet X_{close} \tag{4}$$

If class X is part of a larger system S, then we could statically check the source code of S to see if all calls to X's methods follow the defined expression. If a static analysis is not enough, a runtime verification system can track all calls to X's methods and dynamically check the sequence of calls against the regular expression. This technique can also be used to test the robustness of a system: method sequences that are not derived from the regular expression [3], i.e. incorrect method sequences, can be used to test how the class handles a misuse. For example, to test how the class X responds to the following sequence of calls:

$$X_{create} \bullet X_{close} \bullet X_{process} \tag{5}$$

3 Previous Applications of Message Sequence Specification

Daniels and Tsai [2] extended the work of Kirani and Tsai [3] by testing with some sequences generated by the expression and others not generated by the expression. Also in 1999, Tsai et al. [13] presented Message Framework Sequence Specifications (MfSS), for generating scenario templates that can be used to generate test cases to test applications developed using extensible design patterns and an object-oriented framework. This framework aims to test the dynamic typing and dynamic binding of an Object-Oriented program. MfSS involves multiple objects; thus, a sequence expression must use the object name together with its method name. The framework is suitable for the application of several testing techniques such as positive testing, negative testing, test slicing, partition testing, boundary testing, random testing and stress testing based on scenario templates. The MSS presented in that paper is far more expressive than the one we are presenting but, as far as we know, there is no tool or software that implement this full methodology. The application of the MfSS shown in the original paper was done by hand and not with a software.

In 2003, Tsai et al.[12] used MSS as a verification mechanism to the UDDI servers in the context of Web Services (WS) since they are particularly interoperable with each other. This kind of complex relationship was expressed using the MfSS presented in [13]. This approach was part of a larger set of testing mechanism for WS presented in that work. Unfortunately, the approach was only partially implemented and it did not include the MfSS.

In 2014, a Java-based tool for monitoring sequences of method calls with similar objectives than our work was introduced [10]; however, they used annotations, instead of AOP, to specify method-call sequences in terms of regular expressions of method-call signatures. They included an implementation of the proposal in the form of a tool called JMSeq. This tool runs alongside the application under test, but in a different Java Virtual Machine, hence two virtual machines are running at the same time: one for the program under test and the other for the JMSeq execution. Moreover, since the annotations must be included in the source code of the program to test, these modifications may, potentially, arise new errors. In our approach, AOP avoids the need for modifying the source code, hence reducing the possibility of inducing new bugs.

We introduced MSS as a black-box technique for testing visualizations interactions [7] in 2018. The technique is built on constraints imposed over the sequences of low-level interactions available in the visualization with User Action Notation and MSS. Instead of specifying a sequence constraint on the methods of a class, in this work we specified a Sequence Constraint on the Interactions (SCI) available in the visualization. This research also included the definition of coverage criteria for the technique, both for valid and invalid sequences. The work aimed to generate two types of testing tools: one to dynamically test the correct usage of a visualization tool, i.e. while the user is using the visualization our method checks that the interactions are being used accordingly to the SCI; and the other, to generate the test cases based on the SCI. So far, this research is only available as theory without a proper implementation. Turner used sequence specification for GUI testing in her Ph.D. thesis in 2019, with previous publications about this topic [17], [14], [15],[16]. In these articles, interaction sequences are used as an abstraction of the interactive system to inform a model-based testing approach using lightweight formal methods. Interaction sequences provide an abstract view of the point at which the functional and interactive components intersect. The formalization of interaction sequences and the modelling of those sequences was done using Finite State Automata.

4 TAPIR - An Object-Oriented Programming Testing Framework

TAPIR is a testing framework for object-oriented source code based on MSS and implemented using AOP. AOP allows us, without modifying the source code, to create test cases that execute automatically with each execution of the program under test. The use of MSS allows the developer to describe a regular expression for each class, which represents its correct behavior. The framework executes

the program, and it checks whether the methods are invoked according to the regular expression in the class specification. Thus, TAPIR can be classified as a dynamic analysis testing tool.

A major feature of our framework is to be easy to use, with an easy to read and understand representation of the correct usage of each class' methods. In particular, the user of the framework does not need to be a testing specialist since it was developed to be used directly by the developer. The first thing the developer must do to use the framework is to create the regular expressions associated with the classes under test. These regular expressions must specify the correct behavior or invocation order of the classes' methods. To simplify the regular expression writing, symbols (i. e. characters) are used instead of the actual names of the methods. However, to be able to interpret it, the developer must specify a mapping between the actual methods' names and their corresponding symbol. Any method not included in the class's regular expression is ignored by the framework. Hence, the developer is not required to use all the class's methods in the regular expression. The developer must also specify how the framework should behave in the event of an error. When the framework detects a sequence of calls that does not derive from its associated regular expression, it reports the error and can either abort the execution or allow it to continue. This decision is in the hands of the developer and it can be specified independently for each defined regular expression. The regular expressions and the maps between methods and symbols are set in the *TestingSetup.java* class.

The framework consists of two main components: an aspect, and a java class. The aspect is named *TestingCore.aj* and it contains the implementation of the framework's core. Listing 1.1 shows an example with two classes: CA and CB. In this case, the correct usage of class CA states that, after the creation of the object, there should be a call to *f()* followed by a call to *g()*. After that, there can be as many calls as desired to either *g()* or *h()*. The final call of the sequence must be to *h()*. To correct use class CB, there should be first a call to *alpha()* followed by a call to *gamma()*, or a call to *gamma()* followed by a call to *beta()*. Afterward, any method between *alpha()*, *beta()*, or *gamma()* can be called. Listing 1.1 shows the implementation of the *TestingSetup.java* class that defines this information to TAPIR.

Listing 1.1: TAPIR configuration for classes CA and CB

```
//Class CA: Definition of the methods and their corresponding symbols
mapObjectsToCallSequence = new HashMap<Integer, String>();
mapMethodsToSymbols = new HashMap<String, String>();
mapMethodsToSymbols.put("main.CA.<init>", "c");
mapMethodsToSymbols.put("main.CA.f", "f");
mapMethodsToSymbols.put("main.CA.g", "g");
mapMethodsToSymbols.put("main.CA.h", "h");
//Definition of the regular expression
regularExpression = Pattern.compile("cfg(g|h)*h");
//Initializing the regular expressions controller
matcher = regularExpression.matcher("");
//A TestingInformation instance stores all information related to how the class is tested
```

```
TestingInformation ti = new TestingInformation(CA.class.toString(),
    mapObjectsToCallSequence, mapMethodsToSymbols, regularExpression, matcher,
    true);
TestingCore.mapClassToTestingInformation.put(CA.class.toString(), ti);
//Class CB: Definition of the methods and their corresponding symbols
mapObjectsToCallSequence = new HashMap<Integer, String>();
mapMethodsToSymbols = new HashMap<String, String>();
mapMethodsToSymbols.put("main.CB.alpha", "a");
mapMethodsToSymbols.put("main.CB.gamma", "g");
mapMethodsToSymbols.put("main.CB.beta", "b");
//Definition of the regular expression
regularExpression = Pattern.compile("(ag|gb)(a|g|b)*");
//Initializing the regular expressions controller
matcher = regularExpression.matcher("");
//A TestingInformation instance stores all information related to how the class is tested
ti = new TestingInformation(CB.class.toString(), mapObjectsToCallSequence,
    mapMethodsToSymbols, regularExpression, matcher, false);
TestingCore.mapClassToTestingInformation.put(CB.class.toString(), ti);
```

In Listing 1.3, we can see the framework output when the code portion of Listing 1.2 corresponding to the CA class is executed. In this case, the last call to *f()* does not follow the MSS specified for the *CA* class. As mentioned above, when an error is detected, TAPIR informs by console the class and object that produced the error. The method that violated the MSS, the MSS in question and the actual sequence of calls are also shown in the console. Finally, the system aborts the execution, as indicated by the last parameter of method *TestingInformation* in the configuration.

Listing 1.2: Two snippets of code showing examples of wrong usage of class CA and class CB.

```
CA ca1 = new CA();
ca1.f();
ca1.g();
ca1.h();
ca1.f();
```

```
CB cb1 = new CB();
cb1.alpha();
cb1.alpha();
cb1.gamma();
cb1.gamma();
```

Listing 1.3: Error example for the CA class. The execution is aborted when the error is found.

```
---      ERROR FOUND   ---
Class: class main.CA
Object Code: 977993101
Method Executed: main.CA.f
Regular Expression: cfg(g|h)*h
Execution Sequence: cfghf
----- SYSTEM ABORTING... -----
```

Listing 1.4: Error example for the CB class. The execution is allowed to continue when the error is found.

```
−−−  ERROR FOUND  −−−
Class: class main.CB
Object Code: 859417998
Method Executed: main.CB.alpha
Regular Expression: (ag|gb)(a|g|b)∗
Execution Sequence: aa
−− CONTINUING EXECUTION... −−−
```

```
−−−  ERROR FOUND  −−−
Class: class main.CB
Object Code: 859417998
Method Executed: main.CB.gamma
Regular Expression: (ag|gb)(a|g|b)∗
Execution Sequence: aag
−− CONTINUING EXECUTION... −−−
```

Listing 1.4 shows the framework output when the code portion of Listing 1.2 corresponding to the class CB is executed. In this case, the second call to *alpha*() does not follow the MSS specification for class *CB*. As configured in Listing 1.1, yhe last parameter in the call to method *TestingInformation* is false, indicating that the execution must continue despite the existing errors. This is why, Listing 1.4 shows multiple errors. The next section shows how the framework can be useful in a more complex real-life situation.

5 Case Study. Rock.AR, a software solution for point counting

Point counting is the standard method to establish the modal proportion of minerals in coarse-grained igneous, metamorphic, and sedimentary rock samples. This requires to make observations at regular positions on the sample, namely grid intersections. Rock.AR [5] is a visualization tool with a user-friendly interface that provides a semiautomatic point-counting method and is available as open-source.

5.1 First Detected Bug

The main class of this application contains three important methods: *LoadSample()*, *AddNewRockType()* and *MoveSelectedCell()*. *LoadSample()* loads the rock thin section sample, *AddNewRockType()* links a type of mineral with the selected cell in the grid, and finally, *MoveSelectedCell()* selects a cell in the grid. First, at least one sample must be loaded. Then, before linking a mineral type to a cell, a point (also known as a cell) must be selected. Hence, the following regular expression can be defined:

$$(LoadSample \bullet LoadSample^* \bullet (MoveSelectedCell \bullet MoveSelectedCell^* \bullet AddNewRockType^*)^*)^* \quad (6)$$

or in a simpler way:

$$(l \bullet l^* \bullet (m \bullet m^* \bullet a^*)^*)^* \quad (7)$$

Listing 1.5: Class *TestingSetup* to test Rock.AR with the expression from Equation 7.

```
// Specification of the test class
TestingCore. targetClass = ViMuGenMain2.class.toString();
// Definition of the methods and their corresponding symbols
TestingCore.mapObjectsToCallSequence = new HashMap<Integer, String>();
TestingCore.mapMethodsToSymbols = new HashMap<String, String>();
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.main.ViMuGenMain2.LoadSample", "l");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.main.ViMuGenMain2.MoveSelectedCell", "m");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.main.ViMuGenMain2.AddNewRockType", "a");
// Definition of the regular expression
TestingCore. regularExpression = Pattern.compile("ll*(mm*a*)*");
// Initializing the regular expressions controller
TestingCore.matcher = TestingCore. regularExpression .matcher("");
```

A particularity of this regular expression is that, between loading a sample and adding a new rock type, at least one cell must be selected. We created this regular expression and input it into the framework as shown in Listing 1.5. Once this expression was defined and provided to the framework, we started using Rock.AR. After several runnings, the test framework detected an error and output the sequence of calls that did not comply with the regular expression. The sequence was:

$$l \bullet m \bullet m \bullet a \bullet l \bullet l \bullet a \tag{8}$$

The last three symbols in the sequence indicated that the application allowed a calling to *AddNewRockType()* right after *LoadSample()*, i.e. without calling *MoveSelectedCell()* in between. This calling sequence was not allowed in the regular expression. With this information, we discovered that when the user loaded a second sample, two variables were not re-initialized, causing this incorrect behavior. Before using our framework, there was no evidence of this error. The application did not generate any exception since the program was using old values for those not re-initialized variables.

5.2 Second Detected Bug

In order to help the domain expert to visualize the grid intersection, a colored grid is drawn on top of the mineral image. Each intersection is represented in the implementation by an instance of the class *SampleCell*. Usually, a mineral image requires around 1250 cells. The *SampleCell* class offers methods to set and get the dimensions of the cell and the mineral type. However, once the dimensions are set, they can not be changed. This is because the size of each cell is calculated automatically and the user cannot modify it. Since the mineral type of each cell depends on the user's subjective appreciation, it can change more than once. The following regular expression represents this behavior:

$$CreateSampleCell \bullet (setDimension \bullet setRockType | setRockType \bullet setDimension) \bullet (setRockType | getRockType | getDimension)^* \quad (9)$$

or in a simpler way:

$$x \bullet (d \bullet r | r \bullet d) \bullet (r|w|e)^* \quad (10)$$

As described in this expression, after the creation of the sample cell, both the dimension and mineral type must be set but in no particular order. After that, the mineral type can be set and get as many times as necessary. The dimension, however, can only be retrieved. Listing 1.6 shows the definition of class *TestingSetup* to test RockAR accoding to this regular expression.

Listing 1.6: Class *TestingSetup* to test Rock.AR with the expression from Equation 10.

```
// Specification of the test class
TestingCore. targetClass = SampleCell.class. toString();
// Definition of the methods and their corresponding symbols
TestingCore.mapObjectsToCallSequence = new HashMap<Integer, String>();
TestingCore.mapMethodsToSymbols = new HashMap<String, String>();
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.<init>", "x");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.SetDimension", "d");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.GetDimension", "e");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.SetRockType", "r");
TestingCore.mapMethodsToSymbols
    .put("ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.GetRockType", "w");
// Definition of the regular expression
TestingCore. regularExpression = Pattern.compile("x(dr|rd)(wer)*");
// Initializing the regular expressions controller
TestingCore.matcher = TestingCore. regularExpression .matcher("");
```

As in the previous study case, we ran Rock.AR several times to test the last regular expression. The framework detected an error and output the message shown in Listing 1.7. By inspecting the execution sequence we could see that a mineral type was retrieved from a sample cell without being previously set. This error occurred every time the user loaded a previously saved work.

When users saved their work, Rock.AR only saved to a file the sample cells with a mineral type assigned. The system keeps two arrays, one for all sample cells (with or without an assigned mineral type) and the other to map those sample cells to the assigned mineral type. In order to save the work, the application goes through this mapping array and retrieves those cells with an assigned mineral. The method responsible for this operation had an error in a boolean

condition: instead of iterate until $amount - 1$, it went until $amount$. This error caused the last cell to be always saved on file, with some assigned mineral, even when it had no one associated.

Listing 1.7: Error message by the framework on Rock.AR

```
---      ERROR FOUND   ---
Object Code: 1061804750
Method Executed: ar.edu.uns.cs.vyglab.vimuge.data.SampleCell.GetRockType
Regular Expression: x(dr|rd)(wer)*
Execution Sequence: xdw
----- SYSTEM ABORTING... -----
```

6 Case Study. Earth Defender

Earth Defender is a video game developed in one of our programming courses at the university. It is a classic vertical shooter as Space Invader [1] but with more modern features. It has 28000 lines of code distributed in 217 classes. It was developed in Java 1.8 with Eclipse IDE 4.4. Listing 1.8 shows the setup of TAPIR to test three classes of the system: *PlayerInteractionMananger*, *Enemy* and *GUI_Game*. The *PlayerInteractionMananger* class is responsible for capturing the user interactions that control the space ship's movements and shots. The *Enemy* class's responsibility is to manage each enemy ship of the game; in particular, how each ship returns a power-up when destroyed. Finally, the *GUI_Game* class deals with all the graphical user interfaces of the game.

Listing 1.8: The complete setup method of the TestingSetup class for the Earth Defender game.

```
HashMap<Integer, String> mapObjectsToCallSequence = null;
HashMap<String, String> mapMethodsToSymbols = null;
Pattern regularExpression = null;
Matcher matcher = null;
//Specification of the test class
TestingCore.mapClassToTestingInformation = new HashMap<Integer, String>();

//Testing setup for PlayerInteractionMananger class
//Definition of the methods and their corresponding symbols
mapObjectsToCallSequence = new HashMap<Integer, String>();
mapMethodsToSymbols = new HashMap<String, String>();
mapMethodsToSymbols.put("Main.PlayerInteractionMananger.playerStartMove", "a");
mapMethodsToSymbols.put("Main.PlayerInteractionMananger.playerStopMove", "b");
mapMethodsToSymbols.put("Main.PlayerInteractionMananger.playerShoot", "x");
//Definition of the regular expression
regularExpression = Pattern.compile("((a|b)*x)*");
//Initializing the regular expressions controller
matcher = regularExpression.matcher("");
//A TestingInformation instance stores all information related to how the class is tested
```

```
TestingInformation ti = new
    TestingInformation(PlayerInteractionMananger.class.toString(),
    mapObjectsToCallSequence, mapMethodsToSymbols, regularExpression, matcher,
    false);
TestingCore.mapClassToTestingInformation.put(PlayerInteractionMananger.class.toString(),
    ti);

//Testing setup for EnemyTracker class
//Definition of the methods and their corresponding symbols
mapObjectsToCallSequence = new HashMap<Integer, String>();
mapMethodsToSymbols = new HashMap<String, String>();
    mapMethodsToSymbols.put("Entity.Enemy.takeDamage", "t");
    mapMethodsToSymbols.put("Entity.Enemy.dropPowerUp", "d");
//Definition of the regular expression
regularExpression = Pattern.compile("t*d");
//Initializing the regular expressions controller
matcher = regularExpression.matcher("");
//A TestingInformation instance stores all information related to how the class is tested
ti = new TestingInformation(Enemy.class.toString(), mapObjectsToCallSequence,
    mapMethodsToSymbols, regularExpression, matcher, false);
TestingCore.mapClassToTestingInformation.put(Enemy.class.toString(), ti);

// Testing setup for GUI_Game class
//Definition of the methods and their corresponding symbols
mapObjectsToCallSequence = new HashMap<Integer, String>();
mapMethodsToSymbols = new HashMap<String, String>();
    mapMethodsToSymbols.put("GUI.GUI_Game.inicializar", "a");
    mapMethodsToSymbols.put("GUI.GUI_Game.initLifeBar", "b");
    mapMethodsToSymbols.put("GUI.GUI_Game.initScore", "c");
    mapMethodsToSymbols.put("GUI.GUI_Game.shoot", "h");
    mapMethodsToSymbols.put("GUI.GUI_Game.changeLevel", "i");
    mapMethodsToSymbols.put("GUI.GUI_Game.stopGame", "j");
//Definition of the regular expression
regularExpression = Pattern.compile("((bca(h)*)i)*(bca(h)*)j");
//Initializing the regular expressions controller
matcher = regularExpression.matcher("");
//A TestingInformation instance stores all information related to how the class is tested
ti = new TestingInformation(GUI_Game.class.toString(), mapObjectsToCallSequence,
    mapMethodsToSymbols, regularExpression, matcher, true);
TestingCore.mapClassToTestingInformation.put(GUI_Game.class.toString(), ti);
```

For the *PlayerInteractionMananger* class, the three main methods to test are *playerStartMove*, *playerStopMove* and *playerShoot*. Its MSS is $((a|b)^*x)^*$, where a stands for *playerStartMove*, b for *playerStopMove* and x for *playerShoot*. This means that, under a correct behavior, the player can move several times before shooting. This can be repeated multiple times during a game session. Two methods are considered for the*Enemy* class's MSS; those are *takeDamage*, represented with a t, and *dropPowerUp*, with a d. The MSS for this class is t^*d; this means that each enemy in the game can take much damage until it is

destroyed and drops its power-up. Finally, the *GUI_Game* class has the more complex MSS. Six methods are used: *inicializar* starts the GUI game level, *initLifeBar* draws the life bar on screen, *initScore* draws the initial score of the player on screen, *shoot* draws the shooting effects on screen, *changeLevel* starts the next level once the player completes the current one and, finally, *stopGame* deals with the player's death. These methods are represented by the symbols a, b, c, h, i, and j, respectively. The MSS for the *GUI_Game* class is $((bca(h)^*)i)^*(bca(h)^*)j$. The $bca(h)^*$ part of the MSS represents the user playing a level. If the user wins the level, then he/she moves to the next one. This is shown in $((bca(h)^*)i)^*$. The game continues until the players dies, which is the second part of the MSS, $(bca(h)^*)j$.

6.1 Testing Earth Defender

As Listing 1.8 shows, TAPIR should stop the execution of the game only when it encounters an error on the *GUI_Game* class. If errors are founds on the other two classes, TAPIR will inform them but allow the execution to continue. On the first test run of the game, we played the first level and lost. When we finished playing we found that TAPIR had reported three errors. The output of the framework can be seen in Listing 1.9. The errors correspond to three different objects of the *Enemy* class. We can affirm that they are different objects because the object code that is reported in each error is different. In all three cases, by observing the execution sequence, we can detect that once a ship delivers its power-up, meaning it was destroyed, it still takes new damage. This should not happen since the ship was already destroyed. An analysis of the code involved with this situation showed that the problem was how the enemies were removed from the game. Each time an enemy's life reached 0, the power-up was first delivered, then the score and other features of the game were updated and, finally, the enemy was removed from the level. Since the instance is eliminated last, any other shot that was on the way could still impact it. Consequently, the code was modified to remove the enemy immediately after its life reached zero.

Listing 1.9: TAPIR output of the first test run of Earth Defender

```
−−−  ERROR FOUND  −−−
Class: class Entity.Enemy
Object Code: 1256786520
Method Executed: Entity.Enemy.takeDamage
Regular Expression: t∗d
Execution Sequence: tttdt
−− CONTINUING EXECUTION... −−−
−−−  ERROR FOUND  −−−
Class: class Entity.Enemy
Object Code: 1337065869
Method Executed: Entity.Enemy.takeDamage
Regular Expression: t∗d
Execution Sequence: ttttdt
−− CONTINUING EXECUTION... −−−
```

```
---      ERROR FOUND   ---
Class: class Entity.Enemy
Object Code: 1128333601
Method Executed: Entity.Enemy.takeDamage
Regular Expression: t*d
Execution Sequence: tttttttdt
-- CONTINUING EXECUTION... ---
```

We successfully completed the first level, however, since TAPIR detected errors in the *GUI_class* and it was configured to abort execution in that case, the game closed abruptly at the end of the level. The output of TAPIR can be seen in Listing 1.10. Two errors were found for the same instance of the *GUI_Game* class since the object codes reported are the same. We believe that TAPIR reported two errors that should have aborted the execution because, while processing the first one, the second error occurred. Method *initLifeBar*, represented by the symbol *b*, caused the first error. The last shot of the player can lead to two possible following actions: if with that last shot the player won the level, then the *changeLevel* method must be executed; on the other hand, if after that last shot the player dies, then the *stopLevel* method must be executed. As can be seen in the first error reported by TAPIR, after the last shot, represented in the sequence with *h*, the method *initLifeBar* was executed. As we know that we successfully completed the level, the correct thing would have been the execution of the method *changeLevel*, symbol *i*. The second error reported is a consequence of the first, so correcting the first should fix the second. After inspecting the code, it was discovered that the method *initLifeBar* was called twice each time a level ended. This error was not noticeable from the graphical interface. One of the calls was made after changing levels, this call was correct; the second call was part of the logic that prepares the level change. This line of code should have been deleted in a game update but it was not. By removing this line, both errors detected by TAPIR were corrected. Three more executions of the game were made after this and the framework reported no errors.

Listing 1.10: TAPIR output after the first test run of Earth Defender

```
---      ERROR FOUND   ---
Class: class GUI.GUI_Game
Object Code: 103210007
Method Executed: GUI.GUI_Game.initLifeBar
Regular Expression: ((bca(h)*)i)*(bca(h)*)j
Execution Sequence:
bcahhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhb
----- SYSTEM ABORTING... -----
---      ERROR FOUND   ---
Class: class GUI.GUI_Game
Object Code: 103210007
Method Executed: GUI.GUI_Game.shoot
Regular Expression: ((bca(h)*)i)*(bca(h)*)j
Execution Sequence:
bcahhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhhbh
```

————— SYSTEM ABORTING... —————

7 Conclusions & Future Work

Industry 4.0 requires new methodologies to ensure the quality of its software, a key element in its production chain. Because of this, we present a new testing technique together with a framework that implements it. Our proposal is a testing framework for object-oriented programming. The framework was designed and implemented to detect flaws in the sequence of method calls that objects make. It is suitable for Java projects and can run without modifying the implementation of the project under test. The objective of this framework is to find those vulnerabilities that allow breaking the expected order of execution of the methods of a class. As shown in the case studies, the framework helps with the detection of errors that would otherwise be difficult to find.

As mentioned above, our goal from the beginning was to create an easy-to-use framework for developers to test their Java source code without any modifications, thus reducing setup and testing times and the possibility of introducing new errors. The next step for this line of research is to test the framework with software of an Industry 40 company. For such a case, we have begun to make the corresponding contacts with a company whose solutions are based on blockchain technologies. We hope that the results obtained in this new case can be published shortly. We will also begin to translate our framework into other programming languages with AOP support, such as C# and Python. The framework is available for downloading[1]. The source code is available and licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

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Modelling the Dynamics of a Smart Factory

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Abstract. "Digital twining" is one the main ways of establishing data channels in cyber-physical systems using both the outputs of running a virtual model and real time data collected by sensors. The purpose to this paper is to outline the digital twin of a cyber-physical *production* system. We apply the System Dynamics paradigm to the case of a shop-floor factory devoted to cloud manufacturing. The digital twin uses data from the real production line, providing assistance to maintenance procedures triggered by inconsistencies between the real and the virtual processes.

Keywords: Digital Twin, Cyber-physical Systems, System dynamics, Simulation.

1 Introduction

One of the main components of the Industry 4.0 infrastructure are "smart factories", able to adapt their production processes to demand, assigning their resources more efficiently than traditional factories. The key technologies enabling smart factories are the Internet of Things [2], Cyber-physical Systems (CPS) [3] [4], cloud computing [4] and big data [5] [6].

These technologies allow the efficient integration of different functionalities of the control specification ISA-95 into a single production system. In terms of its five levels, all the processes that can be digitalized can be thus absorbed in Industry 4.0 systems [7] [8]. This integration can be both at horizontal and vertical levels. The vertical integration extends from the physical process level (level 0 of ISA-95) to Manufacturing Execution Systems (level 3 of ISA-95) [9]. These levels, handled by CPS, translate the physical events into digital data, creating a digital twin (DT) of the production system. The digital twin provides useful information about the real workload of the production system, which can be used in planning and business management process-

es [10] [11]. Managers can simulate the inner workings of the plant under different scenarios, gaining further information contributing to make better decisions. The ultimate objective of digital twins is to improve the operation and efficiency of manufacturing assets, reducing costs by forecasting future states and supporting advanced decision-making throughout the entire manufacturing lifecycle [12].

A DT of a production system is a type of simulation that allows the real-time control of production. Ding et al. [1] use the term "digital twining" to refer to the process of building a digital twin in the cyber world of physical objects and systems, establishing data channels for cyber-physical connection and synchronization. The implication of this definition is that a DT should use both simulated values and real time data collected by sensors. The simulation has the ability to compress time running ahead the real world process since the digital twin simulation clock is set at one relevant period ahead of real time. If at time t_r a sensor reports a machine failure that was not generated in the simulation when its internal clock was at t_r, the latter should be reset at t_r updating its state with this new information. This feature enables a DT to keep the simulation running at a par with the real production line.

The aim of this work is to describe a simulation model for a digital twin cyber-physical system. In order to define the guidelines for a smart plant environment, the modelling methodology of System Dynamics can be used to handle the uncertainties and nonlinear relationships among interacting system components [13] [14]. The complexity in the definition of the model may ensue from structural or dynamic aspects. Structural complexity refers to the number of components in a system, or the number of combinations involved in making a decision. Dynamic complexities result from the nonlinear and history-dependent nature of self-organizing and adaptive systems [15]. System Dynamics addresses these two kinds of complexity by postulating that the behavior of complex systems results from an underlying structure of flows, delays, and feedback loops [16]. The emphasis in System Dynamics is not on forecasting the future, but on learning how the actions in a period of time can trigger reactions in the future [17] [18].

The paper is organized as follows. Section 2 presents concepts drawn from the literature on manufacturing processes, providing information about the system to be modelled. Section 3 presents the running example that will illustrate the main notions presented in this article. Section 4 introduces Causal Loop diagrams, the basic graphic modelling tool needed to sketch the description of the system. Section 5 presents Stocks-and-Flow diagrams, which allow developing a full model of the system. Section 6 shows how this model provides the grounds to simulate different scenarios using the digital twin to support decision-making. Finally, Section 7 concludes.

2 Conceptual model of the smart factory

The digital twin concept was first devised as a rich digital representation of actual devices, being widely used in the aerospace field [19]. In 2015, the scope of the original definition was expanded, opening the possibility of using it in other fields [20]. Virtual factories were characterized as the digitalization of plants integrated with the

real systems assisting the production process along the lifecycle of each asset [21]. This development led to two different concepts of what a digital twin is: some researchers believe that it can be identified with its virtual component (i.e. the simulation process) while others emphasize on the connections between the virtual and the physical aspects [22]. Tao *et al.* [23] present a design for a smart factory including four main components: a physical shop-floor (PS), a virtual shop-floor (VS), the data generated by the digital twin (D), and a shop-floor service system (SSS).
The physical part includes entities such as human, machines, and materials. The virtual part refers to the digital twin of the physical shop-floor which supports the decision-making and control of the physical part [23]. It provides control orders for the PS and optimization strategies for the SSS. The data component integrates physical, virtual, and service data with the aim of providing consistent information. The service component embodies services like the definition of production and resource allocation plans as well as guidelines for data fusion. These services, in turn, provide information for both the physical and the virtual shop-floor. The authors propose a three stage operation of the digital twin:

- Before production, the SSS defines a production plan based on data collected from different sources (customer orders, real-time data read by sensors, outputs from the simulation, as well as business data) and transmits it to the VS for verification.
- The VS simulates the production plan and if it works correctly, it sends control orders to the PS to start production. The real-time data generated by the PS is then recorded by the VS.
- Once the production process finishes, its recorded history is analysed to extract knowledge that can be used by the VS to simulate future production plans.

In the digital twin shop-floor framework, physical and simulated data are synchronized. The operational implication is that the simulation is fed with real-time sensor data, sending back controls to the PS in a continuous interaction between the physical and virtual components. Tao et al. [23] framework is the basis for implementing the simulation model of a *digital twin cyber-physical system*. We, in turn, add on top of that the process of updating in real-time the production plan in the context of a cloud manufacturing environment. The ensuing digital twin embodies many specialized digital twins: parts DT, machines DT, and a shop-floor DT. The model assumes the use of real-time production data (shop-floor and cloud-shop floor) to support the factory operations.
While simulation has been traditionally used to identify bottlenecks in production plan, it can now be incorporated into smart machines or tools equipped with devices able to capture, process and transmit data. A simulation fed with such information becomes able to check whether the behavior of the physical factory is consistent with the "simulated" behavior. In particular, when (real) data indicates an unforeseen failure, the simulation synchronizes accordingly (data fusion), updating its behavior, and transmitting new control orders to smart devices. Hence, such simulation of the digital twin cyber-physical system helps to handle failures. Figure 1 depicts our simulation model of a digital twin cyber-physical system.

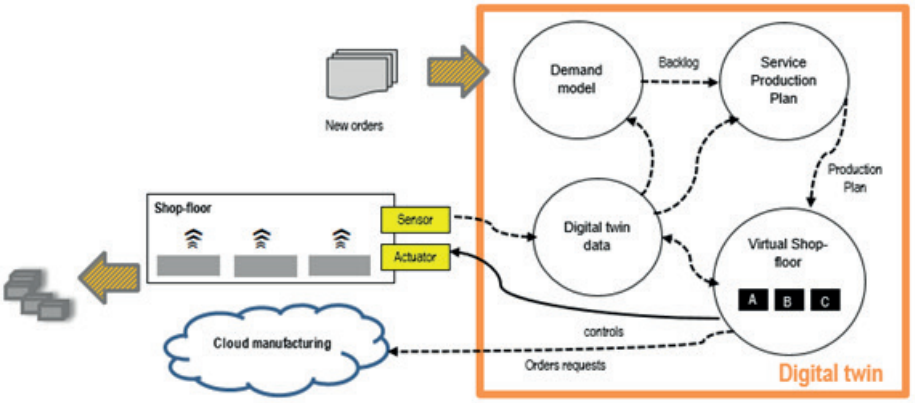

Fig. 1. Simulation model of the digital twin cyber-physical system. Dashed lines: data flow, solid lines: control flow.

3 Running example

Let us consider a smart factory consisting of two production lines A and B. Orders are scheduled on line A. If A is operating above its capacity or it is being repaired, the orders are sent to line B. If line B is operating above its capacity, then the remaining orders are assigned to cloud manufacturing suppliers. For simplicity, we assume that only line A suffers failures and the time to repair is of 3 time units. The cycle times of production lines A, B as well as that of the cloud suppliers are represented by the probability distributions detailed in Table 1. These normal distributions are assumed to have been fitted with historical data of demand.

Table 1. Probability distributions describing cycle time of production facilities.

Production facilities	Cycle time (in days)
A	Normal distribution (mean=2, st. deviation=2%).
B	Normal distribution (mean=4, st. deviation=2%)
Cloud manufacturing suppliers	Normal distribution (mean=2, st. deviation=2%)

4 Causal loop diagrams

The first step towards creating a dynamic model of the digital twin CPS is to draw its Causal Loop diagram [18]. In a Causal Loop diagram variables are connected by arrows denoting the causal influences among them: $x \rightarrow y$ means that the input variable x has some causal influence on the output variable y. A positive influence, denoted by +, means "a change in x, being the rest of variables unchanged, causes y to change in the same direction". In turn, a negative influence means "a change in x, being the rest of variables unchanged, causes y to change in the opposite direction". An increase in a cause variable does not necessarily mean the effect will actually increase

[15]. Since a variable may have more than one input, a change depends on the combined effect of all its input variables. The process wherein one component x initiates changes in other components, and those modifications lead to further changes in x itself is said a feedback loop [24].
According to the system of interest, the diagram may be decomposed in several subdiagrams. For the model of the digital twin cyber-physical system, we developed five diagrams. To save space we include only a partial view of the full causal loop diagram.

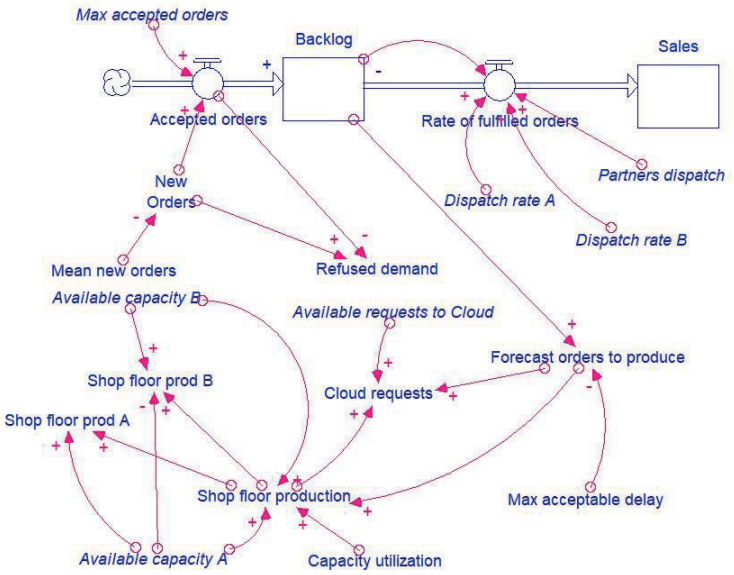

Fig. 2. Causal loop diagram of demand and the production plan. This represents a partial view of the causal loop diagram of the complete system (Generated with Stella™).

Figure 2 depicts the interaction between demand and the production plan. The diagram shows the causal links among the state of the backlog and the accepted orders rate, the dispatch rate of production lines A, B and cloud manufacturing, and the sales volume. As orders increase, the backlog grows, increasing the forecasted number of orders to produce. An increase in the capacity of the production line A adds up the number of units it produces but decreases the shop floor production of line B as well as the production in cloud manufacturing. In turn, increases in failures of production line A decreases its running time and thus its available capacity. As shop-floor production increases, the work in progress and the required dispatch rate grow in time. Finally, increases in the dispatch rate impacts positively on the rate of fulfilled orders and on sales.

The accumulation of resources in a system (stocks), their rates of change (flows) and the feedback loops are the main components of the syntax of dynamic systems models. Stocks are represented by rectangles, inflows and outflows represented by pipes pointing into or out of stocks; valves that control the flows indicate the rates of

change; and clouds represent the sources and sinks for the flows originating outside the boundary of the model. Converters representing processes that convert inputs into outputs are depicted as circles.

5 Stocks and flows diagrams

We structured the smart shop-floor simulation model in five interacting sectors. Cloud manufacturing requests are incorporated in addition to the physical shop-floor production in such a way that production is not limited by plant capacity. The overall structure of interactions between customer demand and flows of orders and products is based on the supply chain models in Sterman [15].

Demand sector. The stock Backlog is the accumulation of accepted orders less the satisfied orders (Fig. 3). It is assumed that orders cannot be changed or cancelled.

$$\text{Backlog}(t) = \text{Backlog}(t-dt) + (\text{Accepted orders} - \text{Rate of fulfilled orders}) * dt \quad (1)$$

There is a cap on the amount of production based on the capacity of the plant and the number of manufacturing orders that can be requested to other manufacturers in the cloud. This cap sets the theoretical maximum production rate that may depend on constraints such as the availability of materials, labor, equipment in the plant and equipment of partners in the cloud. The fulfilled orders rate is given by equation (2).

$$\text{Rate of fulfilled orders} = \text{Dispatch rate A} + \text{Dispatch B} + \text{Partners dispatch} \quad (2)$$

Fig. 3 depicts the Stock and flow diagram for the Demand sector. There are converters and flows defined in such a way as to capture the logic of the synchronization when the behavior of the simulation is not consistent with sensor data. The *Real time gap* is set to 10 meaning that the simulation clock is 10 time units ahead of real time (this value is arbitrarily defined only for illustration). Let the simulation clock be t_s. *Sync backlog* is a variable recording the value of *Backlog* at period $t_s - Real\ time\ gap - 1$. The initial value of converter *Reboot simulation* is 0 and is set to 1 when simulation synchronization is required. Then, if *Reboot simulation* is 1 at simulation time t_s, then the *Backlog* stock is emptied (the flow *Empty Bck* is habilitated) and set to the historical value at $t_s - Real\ time\ gap - 1$.

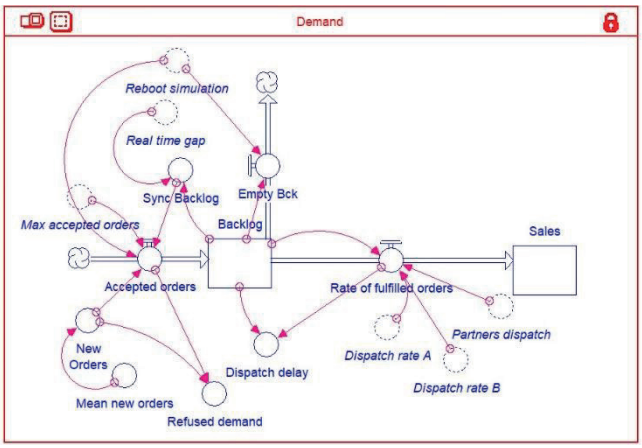

Fig. 3. Stock and flow diagram of Demand (Generated with Stella™).

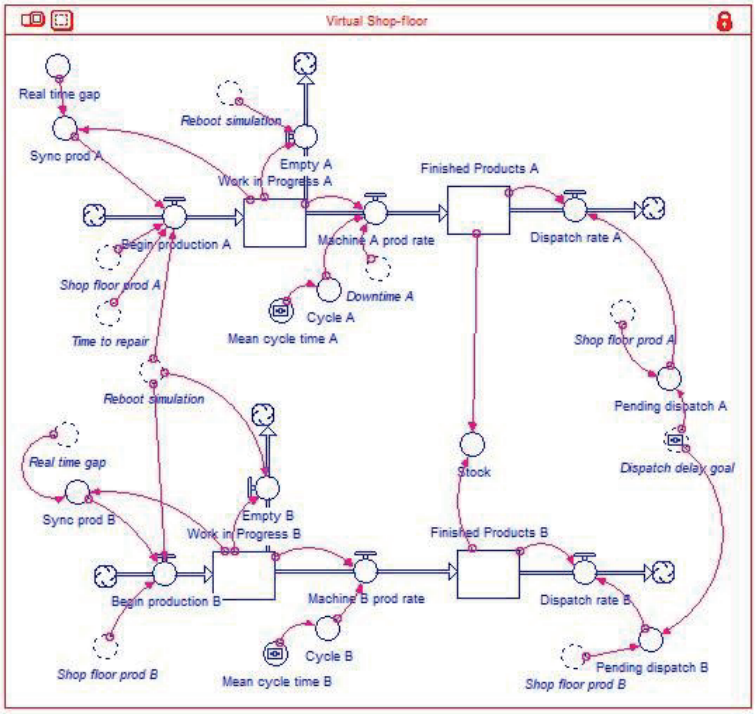

Fig. 4. Stock and flow diagram of the Virtual Shop-floor (Generated with Stella™).

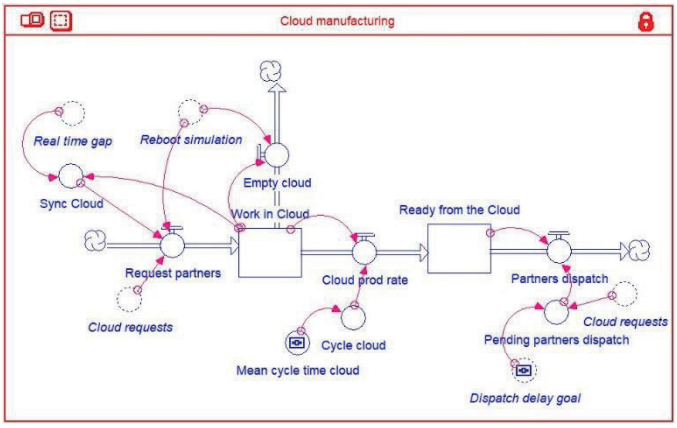

Fig. 5. Stock and flow diagram of Cloud manufacturing (Generated with Stella™).

Virtual shop-floor sector. Production is captured with a chain of two stocks: *Work in progress* and *Finished products* (Fig. 4). For the purpose of this model, all stages of the production process are aggregated together into the *Work in progress* stock as prescribed in Sterman [15].

There are two manufacturing facilities in the plant (A and B) and if necessary, requests are made to cloud manufacturing partners. As mentioned in the description of the Demand sector, there are stocks and flows defined to support synchronization.

Orders are scheduled on production line A. If A is operating above its capacity or it is being repaired, the orders are sent to line B. If also B is operating above its capacity, the required orders are placed to cloud manufacturing providers (Figure 5-8). There exist a maximum of orders that can be requested from the cloud depending on previous agreements with partners. The cycle time is dependent on process-technology and product design (converters *Mean cycle time A*, *Mean cycle time B*). Also, plant A is subject to failure events and the rate of production is thus dependent on the availability of the plant. The stocks, inflows and outflows are formulated as

$$\text{Work in Progress A(t)} = \text{Work in Progress A (t-dt)} + (\text{Begin production A} - \text{Machine A prod rate} - \text{Empty A})*dt \quad (3)$$

$$\text{Empty A (t)} = \begin{Bmatrix} \text{Work in Progress A(t), for Reboot simulation=1} \\ \text{0, for Reboot simulation=0} \end{Bmatrix} \quad (4)$$

$$\text{Machine A prod rate} = \begin{Bmatrix} \text{(Work in Progress A/Cycle A), for Downtime A=0} \\ \text{0, for Downtime A=1} \end{Bmatrix} \quad (5)$$

Most of the time, the inflow *Begin production A* assumes the value *Shop floor production A*. However, when simulation synchronization is required at instant t_s, the simulation should reflect machine A failure at time t_s, and a downtime interval of length $t_s + Time\ to\ repair$, resetting stock *Work in Progress A* with the value at period $t_s - Real\ time\ gap - Time\ to\ repair$ (value recorded by converter *Sync prod A*). Hence, the inflow *Begin production A* is defined as

$$\text{Begin production A(t)} = \begin{Bmatrix} \text{Sync prod A(t-Time to repair), if (Reboot simulation(t)=0} \\ \text{AND Reboot simulation(t-Time to repair)=1)} \\ \text{Shop floor production A(t), otherwise} \end{Bmatrix} \quad (6)$$

We assume that products are dispatched taking into account the dispatch delay goal. For example, if the dispatch delay goal is set to be 3 days and current time is t_s, then finished products which orders were placed at time $t_s - 3$ become dispatched.

$$\text{Finished products A (t)} = \text{Finished products A (t-dt)} + (\text{Machine A prod rate-Dispatch rate A})*dt \quad (7)$$

$$\text{Dispatch rate A} = \text{Min (Pending dispatch A, Finished products A)} \quad (8)$$

$$\text{Pending dispatch A(t)} = \text{Shop floor production A(Max(0, t-Dispatch delay goal))} \quad (9)$$

The dispatch delay takes into account the time since an order is included in the backlog until it is ready for dispatch.

$$\text{Begin production B} = \begin{Bmatrix} \text{0, for Reboot simulation=1} \\ \text{Sync prod B(t-1),} \\ \text{for (Reboot simulation=0 AND Reboot simulation(t-1)=1)} \\ \text{Shop floor production B, otherwise} \end{Bmatrix} \quad (10)$$

Service production plan sector. This sector is in charge of recommending orders of production to each production line (Fig. 6). The number of orders to produce is dependent on the dispatch delay goal and on the available capacity of production lines A, B and of the cloud manufacturing providers. Calculations use data provided by (a) simulations (the available capacity of production lines A and B), and (b) production managers (capacity utilization and the dispatch delay goal).

$$\text{Max acceptable delay} = \text{Dispatch delay goal} \quad (11)$$

$$\text{Forecast orders to produce} = \text{Backlog}/\text{Max acceptable delay} \quad (12)$$

The following formulas represent the scheduling criteria for production lines A, B and cloud manufacturing. The production volume is based on forecasts, assuming that no more than the available capacity is allowed.

$$\text{Shop floor production} = \text{Min ((Available capacity A + Available capacity B)*Capacity utilization), Forescast orders to produce)} \quad (13)$$

$$\text{Shop floor production A} = \text{Min (Available capacity A, Shop floor production)} \quad (14)$$

$$\text{Shop floor production B} = \begin{cases} \text{Min(Available capacity B, Shop floor production-Available capacity A),} \\ \text{for (Shop floor production>Available capacity A)} \\ \text{0, otherwise} \end{cases} \quad (15)$$

$$\text{Cloud requests} = \text{Min(Available requests to cloud,Max (Forecast orders to produce-Shop floor production, 0))} \quad (16)$$

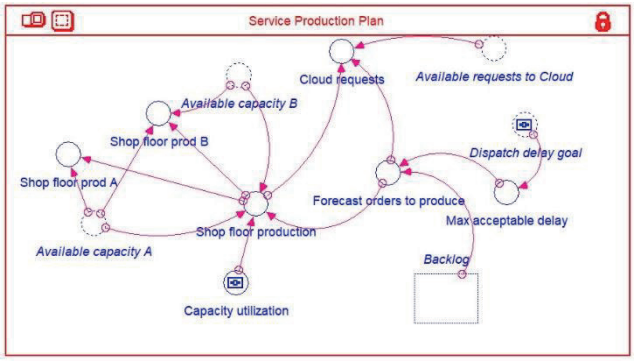

Fig. 6. Stock and flow diagram of Service Production Plan (Generated with Stella™).

Digital twin data sector. The digital twin data sector emulates (Fig. 7) the digital twin data component introduced by Tao [23]. This component is in charge of calculating measures used by the Service Production Plan and the Virtual Shop-floor. These measures are ratios between the capacity utilization of plants A and B, the number of orders that can be requested to cloud partners, and the maximum number of order that can be accepted considering the current level of utilization of plants A and B and cloud services. The dispatch performance rate compares the current dispatch delay and the dispatch goal defined by the firm's goals. The time to repair machine A is defined as constant, but it can be also represented with a probability distribution function or can be a simulation input entered by the operator.

The most relevant part of the digital twin sector is the comparison between data retrieved by sensors and simulated data. For simplicity, we only consider a sensor for machine A (converter *Sensor A*). The sensor detects machine A failures. If this information does not agree with simulated data (converter *Failure A*) at period t_r, then the behavior of the simulation after t_r should be updated to take into account this (the converter *Reboot simulation* is set to 1). In a more realistic setting, the presence of failures should be checked on a time interval (not a point interval).

$$\text{Reboot simulation(t)} = \begin{cases} \text{1, for Sensor A AND (Failure A(t-Real time gap)=0} \\ \text{0, otherwise} \end{cases} \quad (17)$$

The current available capacity of machine A is restricted to its maximum (physical) capacity. In addition, the downtime in case of failure and the reboot of the simulation are also taken into account.

$$\text{Available capacity A} = \begin{cases} 0, \text{ for Downtime A}=0 \text{ AND } \begin{pmatrix} \text{Reboot simulation}=0 \text{ AND} \\ \text{Reboot simulation}(t\text{-Time to repair})=1 \end{pmatrix} \\ \text{Max(Initial capacity A-Work in Progress A, 0), otherwise} \end{cases} \quad (18)$$

$$\text{Available capacity B} = \begin{cases} 0, \text{ for Reboot simulation}=1 \\ \text{Max(Initial capacity B-Work in Progress B, 0), otherwise} \end{cases} \quad (19)$$

6 Scenario modelling

By using the System Dynamics diagrams as a modeling tool and its derived equations we are in conditions of computing numerical solutions. Tools such as Stella™ allow automatizing this computation. There are many techniques of numerical integration of differential equations that can be used to solve the resulting system. The most popular are the Runge-Kutta methods, although their use of finite steps and the approximation to average rates over the interval introduce errors, affecting the results.

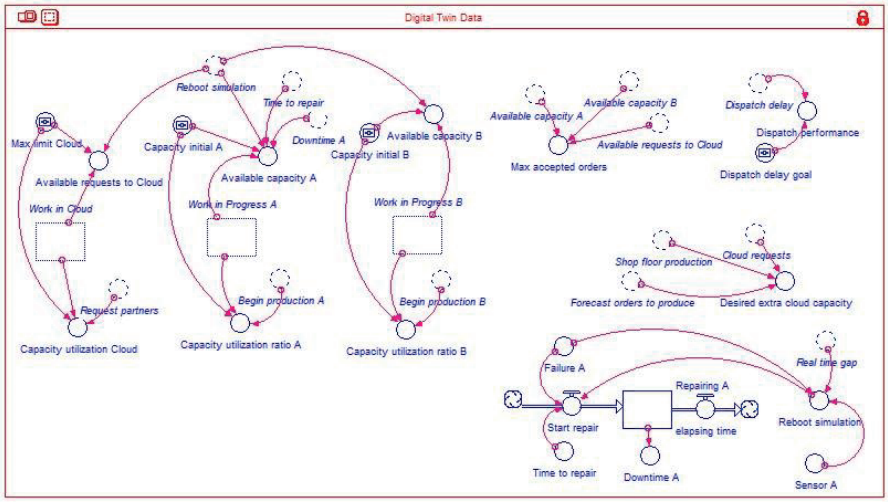

Fig. 7. Stock and flow diagram of Digital twin data. Source (Generated with Stella™).

Table 2. Parameters for the scenario simulation

Parameter description	Value
Demand (number of orders)	Normal distribution (mean=500, st. deviation=10%)
Dispatch delay goal	3 days
Initial capacity of line A	500 units
Initial capacity of line B	400 units
Available cloud capacity	1000 units

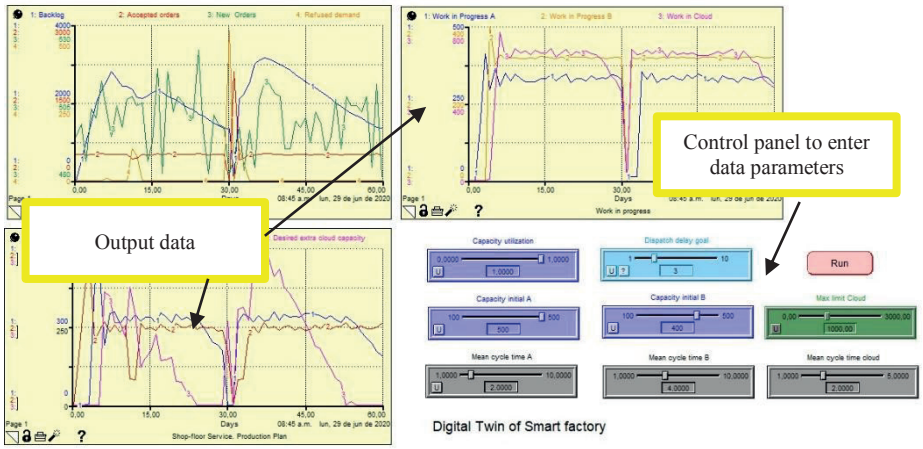

Fig. 8. Digital twin interface including graphics depicting the state of the smart factory and slider input devices to set values of capacity utilization, dispatch delay goal, initial capacity of production lines A and B, maximum limit of requests to cloud manufacturers, and mean cycle times (Generated with Stella™).

Running our system we find that during the first five days, the system is unstable and dominated by the details of the initial conditions. So this period is discarded for analytical purposes. There is a simulated failure of production line A at time 10 and the line is down for 3 days. There is an increase in line B and cloud production (Fig. 9).

There is a failure of line A (detected by sensor data) at real time 20 (the simulation clock is set 10 units ahead of real time). Since the simulation behavior did not consider a failure at time instant 20, then production lines A, B and cloud are set to 0 and re-initialized with real values recorded at simulation time 20 (Fig. 9). In addition, line A is down for 3 days. Simulation forecasts are "corrected" by incorporating real time data when available. Hence, a synchronization of the physical and virtual factory takes place. The available cloud capacity is not enough (notice that *Desired cloud capacity* in Fig. 10 increases after the simulated failure at period 10 and after synchronization due to a real failure of A). This suggests that during downtime plant periods (or an abrupt increase in demand), improving the access to more cloud providers would be recommended. The maximum acquired cloud capacity is not enough to satisfy the desired dispatch delay of 3 days.

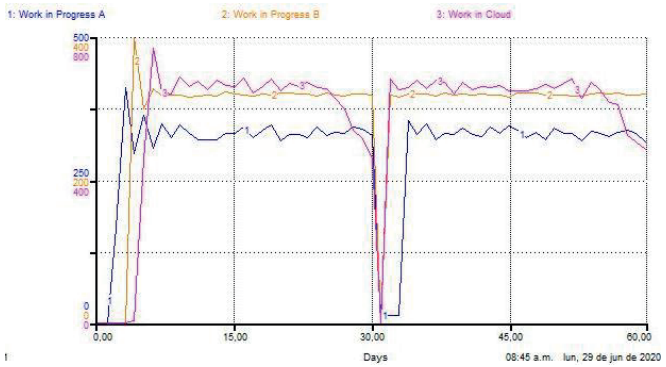

Fig. 9. Production of lines A, B and cloud partners (Generated with Stella™).

In [25] the authors use sensitivity analysis to evaluate the way that behavior patterns vary with different parameters values. We do this to assess the impact of different levels of cloud manufacturing capacity. An increase in that variable would reduce the number of rejected orders. At the same time, such increment entails higher costs incurred in partner agreements.

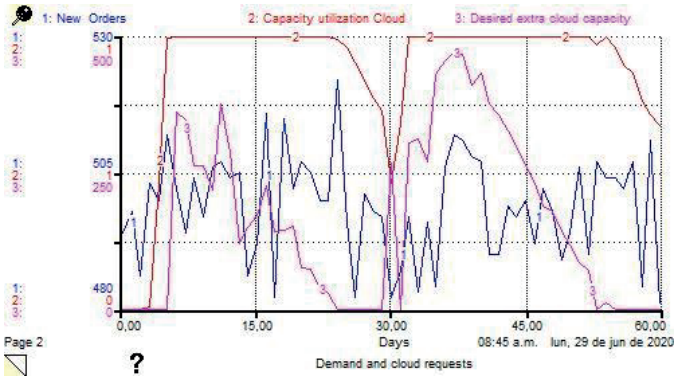

Fig. 10. Demand represented by the *New orders* line; cloud manufacturing capacity utilization (between 0 and 1); and desired extra cloud capacity (defined as the difference between forecasted production orders and available shop-floor and cloud capacity) (Generated with Stella™).

7 Conclusions

The purpose to this paper was to lay down the guidelines for a digital twin of a cyber-physical production system based on a System Dynamics approach. Although we did not intend to cover all systems that may interact with the digital twin, we described how to synchronize the simulation when an inconsistency is detected when

data comes from different sources (data retrieved from sensors and simulated data). It is possible to extend the model to integrate the digital twin with different databases of the organization.

Due to the anticipatory nature of simulation runs, different production plans can be examined to choose the most convenient one according to criteria like optimizing cost, dispatch rate or rejected orders. This information may be useful to support human decision-making or to control a physical machine. This enhances the value of a digital twin (simulation) by supporting real-time production control.

Other simulation paradigms can be used to model and implement a digital twin. For example, discrete event simulation [26] is adequate to model the shop-floor production lines. However, a digital twin of a cyber-physical production system is a complex system (many components or subsystems interact and the knowledge of the impact of a change in a variable over another is incomplete). To model problems with such levels of uncertainty an iterative learning process and modeling tools able to deal with incomplete information are required [18]. The model presented in this work serves as a basis to add interactions with other subsystems belonging to different tiers of the supply chain.

The system dynamics paradigm is adequate to model uncertainty and study the evolution of the system over time (for example, the interactions among demand, logistic disruptions, and machine fatigue). System dynamics shows its potential in forecasting or understanding the far future. Hence, a promising approach is to use an hybrid method based on discrete event simulation to handle short term phenomena (machine failure) and system dynamics comprising all subsystems and assess the far future.

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Integración de ROS y Tecnomatix para el desarrollo de gemelos digitales en sistemas de manufactura flexible

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Resumen. Los gemelos digitales emplean la simulación en conjunto con una variedad de datos provenientes de diferentes equipos y sistemas físicos de planta, para mantener actualizados continuamente sus modelos digitales del mundo en un esquema de retroalimentación en un entorno virtual que facilita la toma de decisiones. La heterogeneidad de hardware y software existente requiere del desarrollo de arquitecturas de software para que los diversos componentes se integren e interactúen mediante el intercambio de información. En este trabajo se propone el diseño y construcción de una arquitectura de software que integra un simulador de procesos de manufactura con el sistema operativo de robots (ROS-*Robot Operating System*). La propuesta se prueba con el simulador *Tecnomatix* de *Siemens*® y la distribución libre ROS *Melodic*. Se presenta una instancia de la arquitectura de software para un caso de estudio complejo típico de plantas de manufactura y se demuestra su fácil integración con un sistema autónomo de toma de decisiones.

Palabras Claves: *Gemelo Digital, Industria 4.0, ROS, Tecnomatix*

1 Introducción

Debido al crecimiento exponencial de la tecnología, los hábitos de consumo globales manifiestan una tendencia cambiante que exige un ritmo cada vez más rápido de adaptación de las industrias de manufactura para poder atender una demanda variable que requiere multiplicidad de productos para ser satisfecha y una producción más personalizada. Esto lleva a los sistemas productivos a buscar una alta flexibilidad y capacidad de reconfiguración, por ejemplo utilizando recursos y/o servicios rentados [1]. En contrapartida, estos sistemas son cada vez más complejos, ya que generalmente reúnen otros sub-sistemas automatizados y/o robóticos para la realización de múltiples tareas a lo largo de todo el proceso productivo [2]. Por lo tanto, en esta nueva

configuración de sistemas de producción existen inevitablemente interferencias dinámicas asociadas con diversas fuentes, como por ejemplo la aleatoriedad de los pedidos de los clientes, la dinámica de la demanda de producción, la baja repetitividad del proceso productivo, el uso de servicios y recursos externos, etc. que hacen que la producción sincronizada pueda verse perturbada en detrimento de la efectividad de respuesta del sistema productivo [3].

Para analizar el comportamiento y el desempeño de los sistemas de manufactura, se ha adoptado la simulación como base para representar sistemas complejos a través de modelos simples y fáciles de comprender [4]. Una variedad de modelos de simulación han sido construidos como base para la toma de decisiones en la industria de manufactura [5]. Así, la simulación se convirtió en una de las herramientas utilizadas, por excelencia, para analizar el impacto de las decisiones tomadas sin afectar la operación del sistema real [6].

En las configuraciones actuales de los sistemas productivos intervienen una variedad de equipos, recursos de software y hardware y, también, recursos humanos que deben actuar coordinadamente y de forma autónoma para hacer frente a la variación y alta frecuencia de las tareas de producción causadas por los requisitos personalizados de los clientes [7]. En este contexto, el paradigma de simulación clásico (dinámica y de eventos discretos) ha dejado de ser el componente central para la formulación de sistemas autónomos de toma de decisiones debido a su característica estática. Por ello, y dada la fuerte irrupción de internet industrial de las cosas junto a los sistemas ciberfísicos [8], su lugar ha sido ocupado por el concepto de gemelo digital (GD) [9]. Sin embargo, los métodos y técnicas de simulación de sistemas tienen un papel preponderante para la abstracción y representación de los sistemas productivos [10]. En este sentido, los GDs emplean la simulación en un esquema de intercambio de información con una variedad de datos provenientes de los diferentes equipos y sistemas físicos, para mantener actualizados continuamente los modelos digitales con el fin de reflejar cualquier cambio que ocurra en los equivalentes físicos en el tiempo[11]. De esta manera, se puede lograr un esquema de retroalimentación en un entorno virtual adaptativo que facilita la toma decisiones apoyándose en estos GDs.

Hasta ahora, la integración entre diferentes tecnologías para el desarrollo de los GDs es una cuestión que ha sido abordada de una forma heterogénea y algunos trabajos han puesto el foco en organizar algunos conceptos claves [11], [12], cuestión que es de vital relevancia para la formulación de propuestas que empleen el uso de gemelos digitales, como por ejemplo en el desarrollo de sistemas de manufactura flexible [13]. Recientemente en el trabajo [14], se formuló una propuesta de arquitectura modular para implementar GDs, probándolo en un clasificador (*sorter*) pequeño y analizando los tiempos de la comunicación entre partes; y en el trabajo [15] realizan una propuesta de integración entre un simulador de eventos discretos y un software de dinámica de sistemas para resolver un caso de un problema de control. En este trabajo, se presenta una arquitectura software para el desarrollo de GDs mediante la integración del bien conocido sistema operativo de robots (ROS) y un simulador de procesos de manufactura flexible, el *Tecnomatix Plant Simulation – Siemens*® (TPS).

2 Metodología

En esta sección introducimos brevemente los principales componentes metodológicos hacia la formulación de un GD para un sistema de manufactura flexible. Para más detalle, el lector podrá referirse a las citas oportunamente indicadas.

2.1 Simulación

La metodología de simulación se ha transformado en una herramienta de análisis indispensable para evaluar el impacto de cambios sin que sea necesario modificar el sistema real. Particularmente, los sistemas de producción manufacturera son un caso especial de sistemas dinámicos híbridos, conocidos como sistemas de eventos discretos [14]. En este sentido, pueden ser modelados y simulados bajo el paradigma de simulación de eventos discretos [6]. La simulación de eventos discretos es una herramienta de análisis ampliamente difundida en el ambiente empresarial y ha comprobado su utilidad para apoyar la toma de decisiones relacionadas con la planeación de la producción e inventarios así como con el diseño de los sistemas de producción y sus cadenas de suministro [5].

Los modelos de simulación representan procesos y situaciones complejas de la realidad en función de los eventos que puedan ocurrir, por lo que pueden representar, tanto situaciones típicas de un proceso productivo (rotura de inventarios, fallas de equipos, aparición de imponderables), como así también estimar un determinado nivel de utilización de recursos relacionados con dichas situaciones. Asimismo, contempla las probabilidades de que ocurran cada uno de los eventos según se asocian con las características de cada uno de los elementos que intervienen. En su conjunto, todos estos elementos simulan la evolución natural del proceso analizado. De esta forma los modelos permiten conceptualizar sobre un proceso productivo y su gestión en términos de los eventos que puedan suceder y cuyo impacto afecta tanto a los clientes como a otros componentes del sistema (p. ej., el uso de recursos). En definitiva, la simulación de eventos discretos es una técnica que se puede utilizar para estudiar los sistemas y procesos cuyos estados van cambiando con el tiempo de forma discreta.

2.2 Gemelos digitales

La irrupción de los sistemas ciberfísicos ha cambiado paradigmáticamente la forma en que se conciben los sistemas industriales, permitiendo la integración de todas las entidades que intervienen en un sistema productivo [15]. Así, es posible lograr la integración y la interacción en tiempo real entre los diferentes componentes de un sistema productivo lo que hace posible gestionar las entidades físicas de manera confiable, segura, colaborativa, robusta y eficiente [16]. Desde esta perspectiva, los sistemas de fabricación integrados podrían pensarse compuestos por dos partes principales: una parte física y una parte digital. Como se muestra en la Fig. 1, la parte física comprende todas las entidades y recursos empleados para la fabricación mientras que la parte digital contiene aplicaciones y servicios ubicuos, incorporando subsistemas con capa-

cidades para el procesamiento y gestión de datos, simulación y análisis junto a sistemas inteligentes para la toma de decisiones.

En la parte física, representada esquemáticamente en la parte inferior de la Fig. 1, se encuentran interconectadas las diferentes entidades involucradas en el proceso de producción y, en una clasificación general, pueden ser agrupadas como Equipos, Materiales, Operarios y Herramientas. Todas estas entidades pueden compartir información y mantener actualizado su estado en tiempo real gracias a las diferentes tecnologías actuales como, por ejemplo, los protocolos Ethernet, ROS, sistemas de georeferenciación, etiquetas/lectores RFID, etc. De esta forma, en la parte física no sólo se recopilan e intercambian datos, sino que también se comunica con la parte digital donde se generan decisiones o acciones que posteriormente se ejecutan en la parte física. Es decir, mediante esta comunicación, la parte digital puede afectar los procesos físicos y viceversa.

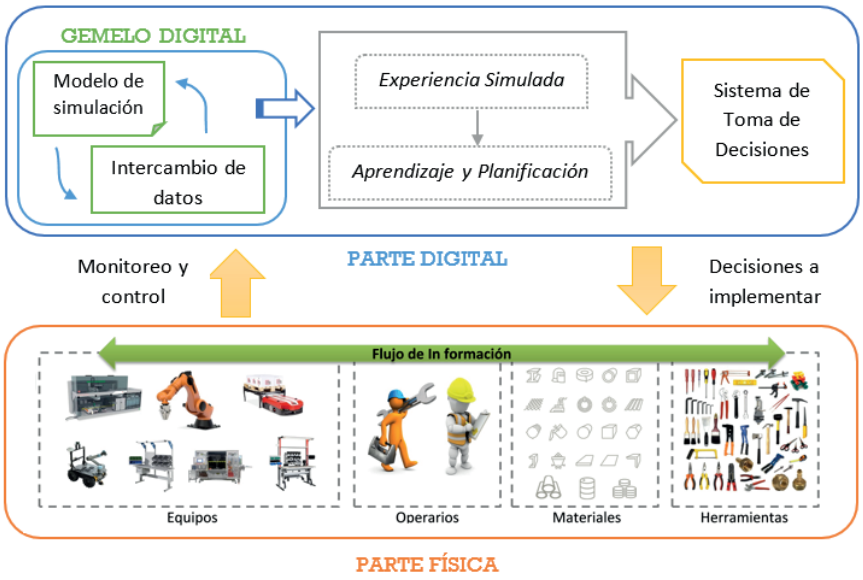


Fig. 1. Entidades y relaciones para un sistema de manufactura flexible.

La parte digital, representada en el fragmento superior de la Fig. 1, contiene distintos subsistemas, servicios y aplicaciones que desarrollan distintas funciones que permiten a las entidades intervinientes en la fabricación operar coordinadamente para optimizar el desempeño del sistema productivo en su conjunto. Actualmente, muchos campos de investigación enfocan sus esfuerzos hacia el desarrollo de propuestas para este sistema virtual. Particularmente, todos ellos buscan aprovechar las bondades y beneficios de diferentes metodologías para generar propuestas que sustenten el desarrollo de sistemas autónomos de toma decisiones, los cuales deben establecer las acciones que se deben ejecutar para gestionar el sistema físico de producción [18]. En este sentido, el concepto de GD ocupa un lugar clave y está centrando la atención de

muchas investigaciones para el desarrollo de metodologías y técnicas que permitan la creación de manera fiable de tales GDs [19].

La función principal de los GDs es proporcionar una descripción física, funcional e integral del sistema en su conjunto. Los GDs son modelos virtuales para reproducir de manera realista las propiedades, comportamientos y reglas de las entidades de la parte física [20]. En otras palabras, los modelos virtuales y las entidades físicas tienen una apariencia y comportamientos similares, es decir, son *gemelos*.

Para el desarrollo de los GDs, las técnicas de simulación tienen un rol central y deben operar en un esquema de intercambio de información con una variedad de datos, provenientes de los diferentes equipos y sistemas físicos de planta, para mantener actualizados continuamente los modelos digitales con el fin de reflejar cualquier cambio que ocurra en los equivalentes físicos en el tiempo. La interacción entre el mundo físico y los GDs tiene una importancia clave debido a que los modelos virtuales y el mundo físico deben evolucionar conjuntamente, ya que este último posee un comportamiento dinámico y, por ejemplo, una misma entidad puede mostrar diversas propiedades en diferentes momentos. Por esto, los datos recogidos en tiempo real del mundo físico se deben compartir con el mundo virtual en un esquema sincronizado para mantener actualizados los modelos virtuales que permiten simular el proceso físico y su evolución.

2.3 Jerarquía de los Gemelos Digitales

Desde una perspectiva jerárquica, los GDs pueden pensarse compuestos por tres niveles diferentes: Entidades, Información y Sistema.

En un primer nivel se encuentran los modelos de todas las entidades que intervienen en el sistema físico. En este nivel, cada una de las entidades debe ser modelada digitalmente con la mayor fidelidad posible. Actualmente, existen muchas soluciones y plataformas disponibles empleadas en el ámbito industrial que proveen soluciones para cada una de las entidades. En concreto, para diferentes tipos de entidades se han desarrollado potentes simuladores computacionales que ya han dado cuenta de su eficacia. También, es común que intervengan personas para desarrollar tareas específicas, los cuales pueden ser modelados digitalmente, empleando un simulador adecuado [7]. De la misma forma, cuando intervienen entidades que realizan operaciones unitarias pueden ser modeladas mediantes entornos de simulación específicos. En definitiva, una vez que se identifican todas las entidades intervinientes en el proceso productivo, cada entidad puede ser comprendida como un subsistema dentro de otro sistema más amplio, y a su vez, existen herramientas computacionales de simulación que permiten crear los modelos digitales más apropiados de cada una de ellas.

Cada uno de los subsistemas modelados no opera de manera aislada, sino que tiene asociado un comportamiento en el que realiza intercambios (por ej. de materiales, energía, insumos, datos, etc.) con otras entidades en el proceso productivo. Es decir, cada una de las entidades presentes tiene un propósito específico y, en consecuencia, tienen asociados un conjunto de funciones con lo cual continuamente están generando datos y/o información que pueden ser almacenados y/o compartidos entre las distintas entidades físicas y sus modelos digitales.

En el sistema productivo, las entidades están relacionadas y comparten datos e información, es decir tienen una relación sinérgica y son parte de una estructura sistémica. Por ello, cada una de estas entidades debe estar adecuadamente modelada y vinculada entre sí cuando se genera el modelo del sistema productivo en su conjunto. En otras palabras, de nada sirve, por ejemplo, modelar perfectamente y de forma aislada un centro de trabajo, un robot manipulador y un operario si no se lo hace con todas las relaciones y propiedades requeridas en el entorno fabril en el que se están empleando.

Dada la heterogeneidad y la complejidad de las entidades que pueden intervenir en un sistema de manufactura flexible y por lo tanto, para generar los mejores GDs, es conveniente utilizar los simuladores específicos y adecuados para cada entidad acorde a su complejidad y especificidad. En el desarrollo de GDs para sistemas completos de producción manufacturera, la vinculación entre diferentes entornos de simulación y las entidades físicas ha sido poco desarrollada en la literatura. Por ello, en este trabajo se propone una arquitectura de software que permite integrar diferentes entornos de simulación, útiles para modelar cada una de las entidades comúnmente usadas en los entornos de manufactura flexible, así como con los dispositivos físicos propiamente dichos. Esta propuesta se desarrolla en la próxima sección.

3 Integración Tecnomatix & ROS

Hoy en día, es muy común que los fabricantes de robots y equipos automatizados para la industria provean simuladores computacionales de sus productos, los cuales son la base para la creación de los GD de cada equipo o entidad en cuestión. Sin embargo, muchas de estas soluciones disponibles no ofrecen una solución integral desde la perspectiva del sistema industrial. La diversidad y complejidad de cada una de las entidades que intervienen en un proceso productivo hacen que los simuladores destinados a modelar íntegramente un sistema productivo (por ejemplo los simuladores de eventos discretos), puedan no reflejar con suficiente grado de fidelidad el sistema en su conjunto ya que tienden a simplificar la dinámica de las entidades que lo componen, lo cual va en detrimento de la calidad de un GD del sistema industrial que se pretenda crear. Por esto, la integración de un simulador de eventos discretos con las entidades reales junto con sus simuladores especializados, representa una opción prometedora para la creación de un verdadero GD de un sistema industrial.

3.1 El Sistema Operativo Robot - ROS

En el pasado, la interacción y la comunicación con y entre los robots eran complejas y dependientes de la plataforma robótica empleada. Durante la última década, esta situación ha sido facilitada y potenciada debido al creciente desarrollo del Sistema Operativo Robot, conocido como ROS[1].

[1] https://www.ros.org/

ROS consiste de un conjunto de procesos heterogéneos e independientes denominados nodos ejecutados al mismo tiempo y teniendo la capacidad de intercambio de mensajes entre ellos. La conexión entre los nodos se denomina tópico. Un nodo puede publicar mensajes o subscribirse a un determinado tópico [21]. ROS es ampliamente utilizado en la comunidad de diseñadores y fabricantes de robots debido a sus características de software abierto, que permite encapsular nodos desarrollados en diferentes lenguajes de programación, facilitando enormemente el crecimiento incremental del sistema y su prototipado. En efecto, la incorporación de nuevos nodos que manejen nuevos dispositivos, tanto sensores como actuadores, se realiza de forma inmediata y homogénea, aún para dispositivos con drivers realizados en software propietario y muy diferente entre sí. Estas características le confieren a toda la arquitectura una gran versatilidad, fundamentalmente para el trabajo de investigación tecnológica.

Resumidamente, las principales características y ventajas de ROS son: (1) abstracción de hardware y control de dispositivos de bajo nivel; (2) intercambio de mensajes entre procesos; (3) gestión de paquetes; (4) herramientas para desarrollar, probar y ejecutar código en varios tipos de lenguajes de programación; (5) computación distribuida; (6) reutilización de software; y (7) pruebas rápidas. En este sentido, todos los robots equipados con ROS tienen el mismo criterio de comunicación.

Para la creación de los GDs, la estandarización de los protocolos de comunicación juega un papel central. Teniendo en mente que los GDs están constituidos por modelos simulados, con fusión de datos reales, es atinado pensar en la creación de estos gemelos considerando la posibilidad de interactuar con las entidades reales.

3.2 Simulador de planta *Tecnomatix*

En esta sección presentamos brevemente el paradigma de programación del simulador de procesos de manufactura TPS.

Una particularidad que, en principio, vuelve atractivo al software *Tecnomatix* es que, por una parte, se pueden explorar sus capacidades con licencias de prueba libres y con un número máximo de hasta ochenta entidades, lo cual muchas veces es suficiente para modelar, por ejemplo, un sistema productivo de una pequeña/mediana empresa. Por otra parte, permite la interconexión con software y *hardware in the loop* tipo PLC (*Programable Logic Controller*) y la integración con los productos Siemens es aún más sencilla. En la práctica esto puede ser ventajoso dado que es muy común la existencia de este tipo de equipamiento en las plantas industriales.

Finalmente otra de las ventajas que brinda el software del TPS a la hora de modelar es que tiene una interface gráfica amigable que permite modelar un sistema de manufactura simplemente seleccionando cada uno de sus componentes, ubicándolo y estableciendo las relaciones con los demás componentes del sistema. También permite programar lógicas de actuación a cada instancia utilizada con su lenguaje propietario. Asimismo, otra cualidad que lo vuelve aún más atractivo es que cada una de esas instancias permite una conexión directa con Python. Para nuestra propuesta, esto es de suma importancia dado que es posible la conexión con otras instancias cuyo comportamiento sea el del elemento real o su homólogo simulado mediante su específico simulador dinámico.

3.3 Arquitectura de Integración

La Fig. 2, esquematiza la combinación de los elementos individuales descriptos en la secciones previas para desarrollar la arquitectura de software propuesta que integra ROS y el simulador de procesos de manufactura TPS, con la posibilidad del agregado de un sistema de decisión autónoma para optimización de procesos.

Observando en la parte superior izquierda de la Fig. 2, tenemos encerrado en una línea de color gris el ROS. Este componente se encuentra integrado por dos nodos, o procesos heterogéneos e independientes, denominados *roscore* y *Simulación de Planta*. El nodo *roscore* representa generalmente una colección de procesos y programas del ROS que permite que una red heterogénea de nodos puedan comunicarse entre sí. El nodo *Simulación de Planta* representa el proceso que tiene la responsabilidad de dirigir una planta de manufactura simulada. A su vez, este proceso puede comunicarse con otros nodos por medio de tópicos del tipo suscriptores o publicadores. Por ejemplo, el conocimiento de optimización de procesos obtenido en el nodo de *Simulación de Planta* en base a simular una planta de manufactura puede ser publicado directamente a través de un tópico que modifique el comportamiento de una entidad de planta real. Por otro lado, el nodo *Simulación de Planta* puede suscribirse a un tópico de datos proporcionado por una entidad real que altere el proceso de optimización de una planta de manufactura en particular simulada, proporcionando conocimiento que nuevamente puede ser aplicado a una entidad real, teniendo como resultado un GD para un sistema industrial.

Por otro lado en la parte superior derecha de la Fig. 2, se encuentra encerrado en una línea de color celeste el simulador de procesos de manufactura TPS. Con este software es posible diseñar plantas de manufactura adaptadas a cada problemática en particular con el objetivo de simular sus procesos de producción. Cada una de las plantas de manufactura se almacena en archivos externos con extensión .spp. Por ejemplo, en la Fig. 2 se muestra el modelo desarrollado en el simulador TPS para un GD de un problema puntual de manejo de materiales en un piso de planta flexible. Este caso de estudio se aborda en detalle en la Sección 4.

En la parte central de la Fig. 2, delimitada por una línea de color verde, se encuentra la integración entre ROS y el software TPS. Como se puede ver, se propone un patrón de diseño de clases siguiendo el paradigma de programación orientada a objetos para el desarrollo de la arquitectura de software propuesta en este trabajo. El diseño propuesto se implementó y testeo íntegramente utilizando el lenguaje de programación Python. La comunicación entre ROS y el software TPS se realiza mediante la clase denominada *Interfaz de Conexión*, que tiene la responsabilidad de proporcionar puntos de acceso externos que realizan alteraciones dentro del software de simulación. Estos puntos de acceso comprenden la carga de una planta en particular para ser procesada por el simulador, establecer y obtener datos de una entidad cualquiera simulada, comenzar, parar y pausar simulaciones, entre otras alteraciones permitidas por el software TPS. Para implementar esta comunicación se utilizó la librería *win32com* la cual permite intervenir de forma externa cualquier sistema que sea ejecutado dentro del sistema operativo de Windows®. La clase *Interfaz de Conexión* representa el patrón de diseño *Mediator* utilizado comúnmente en el desarrollo de

software de la programación orientada a objetos, el cual tiene la responsabilidad de encapsular la comunicación entre los objetos [22].

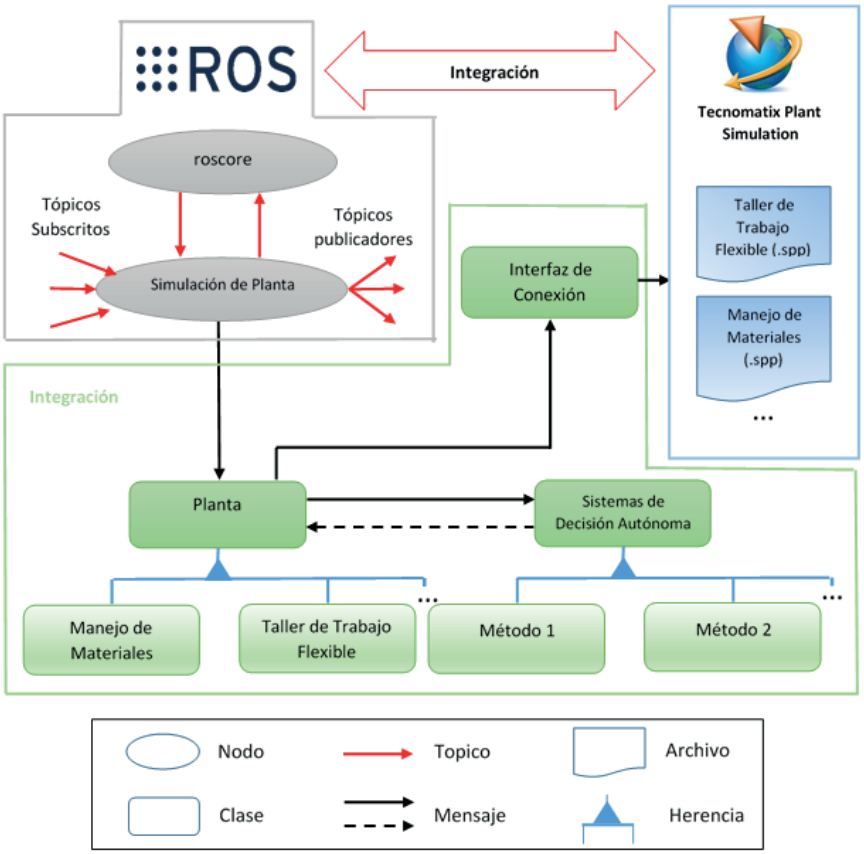


Fig. 2. Arquitectura de software propuesta para integrar ROS y un simulador de procesos de manufactura TPS, con la posibilidad del agregado de un sistema de decisión autónoma.

Siguiendo con el diseño de la arquitectura de software propuesta se observa que el nodo *Simulación de Planta* del ROS ejecuta procesos mediante el pasaje de mensajes, de una planta en particular utilizando la clase *Planta*. La clase *Planta* representa una clase abstracta y sigue el patrón de diseño denominado herencia simple, la cual abstrae todo el comportamiento general de cualquier planta de manufactura simulada [23]. Precisamente, la clase *Planta* ejecuta procesos mediante el pasaje de mensajes por medio de la clase *Interfaz de Conexión*, la cual representa un comportamiento general que requiere cualquier planta de manufactura simulada coordinada externamente. En esta jerarquía simple se tienen por ejemplo dos clases de plantas de manufactura concretas denominadas *Taller de Trabajo Flexible* y *Manejo de Materiales*, entre otras plantas que pueden ser implementadas. Cada planta concreta implementa el comportamiento de coordinación de una planta simulada por el software de simula-

ción. Por ejemplo, la clase concreta *Manejo de Materiales* tiene la responsabilidad de cargar dentro del software de simulación el archivo *Manejo de Materiales* con extensión spp, cambiar el comportamiento de la planta simulada ante establecimiento de datos a entidades simuladas, comenzar, parar y extraer resultados de una simulación, siempre a través de los puntos de accesos brindados por la *Interfaz de Conexión*. Se debe tener en cuenta que cada comportamiento específico de cada clase concreta de planta depende de la simulación abordada para cada planta en particular. Asimismo, debe notarse que la extensión de una nueva planta concreta que dirija de forma externa una planta simulada por el software TPS es directa, simplemente se debe crear una nueva clase que herede de la clase *Planta* y codificar el comportamiento simulado requerido, promoviendo la escalabilidad de la arquitectura de software propuesta.

Paralelamente a la jerarquía de planta, se tiene una herencia simple con la clase abstracta *Sistemas de Decisión Autónoma*. Esta clase abstrae todo el comportamiento general de cualquier método de toma de decisiones autónoma provista por la inteligencia artificial. Una clase concreta, y como se mostrará en la Sección 4, representa la aplicación de un método particular de aprendizaje por refuerzo. Notar, que el agregado de un nuevo método de decisión autónomo es directo, simplemente se debe crear una clase que herede de la clase *Sistemas de Decisión Autónoma* y codificar el método en particular, nuevamente fomentando la escalabilidad de la arquitectura de software propuesta.

Estas jerarquías paralelas interrelacionadas entre las clases abstractas *Planta* y *Sistemas de Decisión Autónoma* representa una combinación de patrones de diseño conocidos como *Factory Method* y *Observer* o *Publish-Suscribe* utilizados comúnmente en el desarrollo de software de la programación orientada a objetos [22]. El patrón *Factory Method* tiene la responsabilidad de construir o fabricar objetos de un subtipo determinado, es decir, plantas simuladas, en la que se le puede o no aplicar dentro de cada subtipo un método en particular, en este caso, un proceso del sistema de decisión autónoma. Por otro lado, el patrón y *Observer* o *Publish-Suscribe* define una dependencia entre el observador (la clase *Planta*) y observado (la clase *Sistemas de Decisión Autónoma*). De esta manera, una planta cualquiera, es decir, el observador, ejecuta un proceso en particular del sistema de decisión autónoma, es decir, el observado (ver Fig. 2 el paso de mensaje de una flecha color negra). Luego, cuando el observado cambia de estado, por ejemplo, cuando el método de sistema de decisión autónoma obtiene un resultado en la optimización de un proceso en particular, el observador es notificado automáticamente (ver Fig. 2 el paso de mensaje de una flecha color negra a trazo), teniendo nuevamente el control de la planta, y a su vez, el resultado del proceso de optimización para que seguidamente altere con el resultado obtenido la planta simulada en cuestión.

Observando con una mirada abstracta la Fig. 2 podemos notar que desde cualquier nodo del ROS podemos crear numerosas plantas de manufactura a la vez de igual o de distinto tipo, que interactúen con el simulador de procesos de manufactura TPS, y a su vez a cada tipo de planta se le puede aplicar o no métodos de un sistema de decisión autónoma.

3.4 Gemelo digital para la TDDs

Como ya hemos señalado, el paradigma de fabricación centrado en el cliente requiere que las empresas se esfuercen en buscar alternativas para mejorar su competitividad. El hecho de desarrollar sistemas autónomos de toma de decisiones (SATDD), capaces de optimizar productividad global del sistema de fabricación y consecuentemente el uso de recursos, es una ventaja distintiva para la determinación de una variedad de decisiones que deben tomarse constantemente, y en tiempo real, para hacer frente tanto a las variaciones de demanda de clientes, como así también, a las perturbaciones propias de un sistema productivo. Los SATDDs, para ser eficaces, necesitan información precisa y en tiempo real para determinar su política de actuación [8].

En el pasado, los modelos digitales se usaban casi exclusivamente para analizar y validar los comportamientos de los sistemas e instalaciones industriales de producción altamente automatizados. En la actualidad, las tecnologías modernas, la digitalización y la inteligencia artificial fomentan la necesidad de desarrollar aún más las herramientas de planificación digital a la vez que promueven el desarrollo de métodos SATDD

La propuesta de desarrollo de GDs para sistemas de manufactura, es justamente, uno de los pilares para el desarrollo de SATDD basados en el paradigma del aprendizaje por refuerzos (AR) [24]. En este esquema un agente inteligente (SATDD) interactúa con su entorno (GD) eligiendo acciones cuyo objetivo es maximizar la recompensa esperada. Formalmente, este problema se describe como un problema de decisión de Markov el cual requiere que se defina un vector de estado del sistema, el conjunto de acciones posibles a tomar en cada estado y una función de recompensa que premie los efectos de las acciones tomadas. En la Sección 4.3 se detalla cada uno de los elementos en base al caso de estudio abordado.

4 Caso de estudio

En los sistemas de manufactura flexible el manejo de materiales es un problema difícil y que afecta directamente la eficiencia y productividad del sistema de fabricación. Mejorar la eficiencia de los procesos complejos de fabricación, en particular la logística y el manejo de materiales, es un problema difícil y que ha recibido especial atención, principalmente para la planificación de tareas en esquemas de producción estáticos. Sin embargo, no hay demasiada evidencia para esquemas de producción dinámicos, cuando cambian por ejemplo, alguna de las condiciones de los pisos de planta flexibles y/o también varía la demanda. En esta sección presentamos la creación de un GD para un sistema de manufactura de manejo de materiales. La creación del modelo digital en el software TPS y su integración con ROS para el desarrollo de los correspondientes GDs, se realizó siguiendo los pasos descriptos en las secciones anteriores. Finalmente, se presentará una propuesta de integración con un sistema de toma de decisiones que emplea un agente artificial de AR.

En un problema de manejo de materiales se busca minimizar las distancias recorridas, el uso de los medios de transporte y las demoras en las entregas que interrumpan el sistema productivo. Durante la resolución de un problema de este tipo, se debe evitar la interrupción del flujo de trabajo asegurando la provisión en tiempo y forma

de los insumos necesarios para las diferentes estaciones de trabajo procurando lograr el normal funcionamiento del sistema de producción.

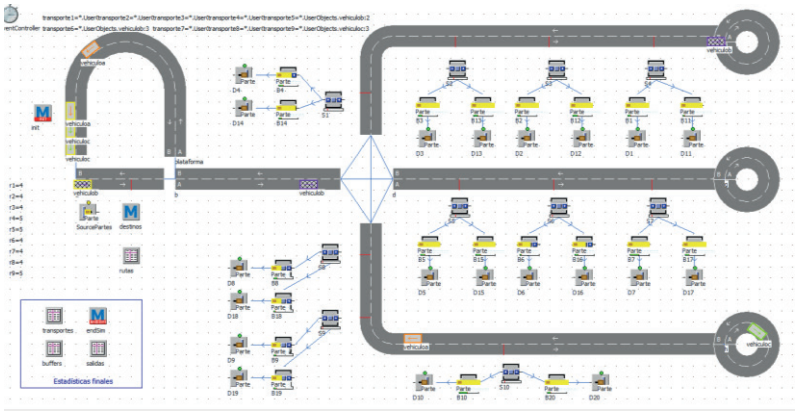


Fig. 3. Modelo de simulación en TPS.

4.1 Definición del modelo de simulación

Particularmente, para el análisis se toma el caso de estudio presentado en el trabajo de [25]. Para más detalles se recomienda recurrir al trabajo mencionado.

El sistema está compuesto por diez estaciones de trabajo ($S_i \; \forall \; i = 1, 2, \dots, 10$) que consumen dos tipos de parte (P_1, P_2) cada una simultáneamente; en cada estación existen buffers ($B_k \; \forall \; k = 1, 2, \dots, 20$) de almacenamiento para cada parte cuyas capacidades son iguales al doble de la cantidad de partes de cada tipo consumidas en una hora; hay nueve vehículos de tres tipos diferentes ($V_{je} \; \forall \; j \in \{1, 2, 3\} \; \vee \; e \in \{1, 2, 3\}$ y se desarrollan distintos planes de manejo de materiales. Cada plan de manejo de materiales tiene asociado una ruta a seguir (W_c), un transporte específico (T_d), partes y cantidades de partes a llevar a las estaciones. Los equipos de transporte no son todos iguales, es decir, cada tipo de vehículo tiene su propia capacidad de carga y puede llevar cualquier tipo de parte.

La Fig. 3 muestra el modelo desarrollado en el software TPS. Como se puede observar, en este modelo están presentes todas las entidades que forman el sistema en estudio. Asimismo se aprecian, las vías de circulación con sus respectivos sentidos, los puntos de carga/descarga, los equipos de transporte y las partes.

4.2 Integración digital

El modelo en el simulador TPS queda definido mediante un conjunto de parámetros, los cuales pueden accederse externamente mediante el nodo ROS creado. La Fig. 4 muestra los resultados finales de una simulación que sirven de entrada a un sistema de toma decisiones. Para poder cambiar los planes se recolectan: distancias recorridas por cada medio de transporte y nivel de ocupación de los mismos (Fig. 4a), nivel máximo de llenado de los buffers respecto a la capacidad definida y porción del tiempo

en que se llenan completamente (Fig. 4b) y porcentajes de trabajo y espera en cada salida que consume partes (Fig. 4c).

string 0	real 1	real 2
string	Distancia recorrida	Porcion ocupado
1	Transporte1	611.93	0.11
2	Transporte2	612.33	0.10
3	Transporte3	628.73	0.11
4	Transporte4	613.13	0.15
5	Transporte5	533.20	0.10
6	Transporte6	629.93	0.10
7	Transporte7	534.00	0.10
8	Transporte8	614.73	0.11
9	Transporte9	1266.86	0.17

(a)

string 0	integer 1	integer 2	real 3
string	Buffer	Capacidad	Max número partes	Porción lleno
1	B1	136	31	0.00
2	B2	178	35	0.00
3	B3	184	86	0.00
4	B4	50	29	0.00
5	B5	80	55	0.00
6	B6	132	32	0.00
7	B7	40	40	0.06
8	B8	30	14	0.00
9	B9	44	12	0.00
10	B10	60	42	0.00
11	B11	158	26	0.00
12	B12	74	31	0.00

(b)

string 0	real 1	real 2
string	Salida	Working	Waiting
1	D1	0.85	0.15
2	D2	0.77	0.23
3	D3	1.00	0.00
4	D4	1.00	0.00
5	D5	1.00	0.00
6	D6	0.86	0.14
7	D7	1.00	0.00
8	D8	1.00	0.00
9	D9	0.91	0.09
10	D10	1.00	0.00
11	D11	0.72	0.28
12	D12	1.00	0.00

(c)

Fig. 4. Resultados obtenidos en el simulador TPS.

4.3 SATDD para el manejo de materiales

A continuación se presentan los elementos para la formulación del problema de AR. A menos que se diga lo contrario, se omite el subíndice t de representación del tiempo a efectos de simplificar la notación.

Estado del sistema

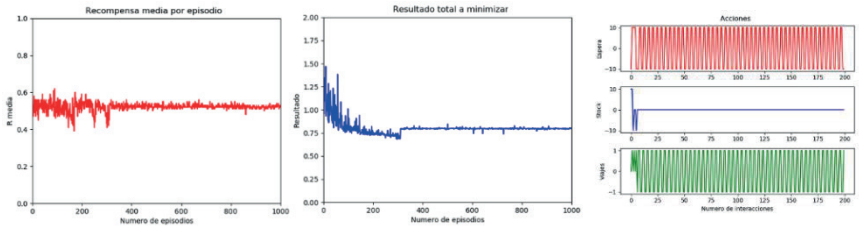
Para la representación del estado, del sistema se consideran las magnitudes de tres de las variables a saber: el tiempo de espera al cargar (T_l), el stock inicial (s_0) y la cantidad de viajes por vehículos (M), manteniéndose constantes los demás parámetros de sistema. De esta manera, el vector de estado del sistema es $\mathbf{s}_t = (T_l, s_0, M)$. Para la discretización del estado del sistema, el tiempo T_l se discretiza con un paso de 10 segundos en el intervalo [60, 300]; el stock s_0 puede tomar valores entre [10, 50] con un paso de 10 unidades; la cantidad de viajes por vehículos debe estar en el intervalo de enteros [1, 5].

Acciones

En cada estado en que se encuentre el sistema el agente podrá aumentar/disminuir en 10 segundos el tiempo de espera en cargar, aumentar/disminuir en 10 unidades el stock inicial y aumentar/disminuir en 1 los viajes por vehículo. En todos los casos, para cada variable, el agente también puede tomar la decisión nula, es decir, no modificar alguna (o todas) las variables de plan. De esta forma, el vector de acción tomado por el agente es $\mathbf{u} = (u_1, u_2, u_3)$, tal que $u_1 = \{-10; 0; 10\}$, $u_2 = \{-10; 0; 10\}$, $u_3 = \{-1; 0; 1\}$.

Función de recompensa

En este problema, se busca optimizar el desempeño del sistema en base al grado de movimientos, uso de los *buffers* y tiempos de espera. De esta forma la función de recompensa planteada devuelve un valor + 1 sí y sólo sí el plan mejora y 0 de otra forma. Para poder evaluar la mejora del plan se comparan resultados en dos momentos sucesivos: $\mathcal{L}(\mathbf{u}|\mathbf{s}) = C_1 w_1 + C_2 w_2 + C_3 w_3$; tal que C_1 es el porcentaje de ocupación de los transportes; C_2 es la porción de tiempo en que los buffers se llenan completamente y C_3 es el porcentaje de tiempo de espera total para consumir las partes. Los factores de peso w_1, w_2 y w_3 se fijaron en 0.3, 0.3 y 0.4, respectivamente. Si el resultado disminuye respecto al anterior, entonces se confirma la mejora del plan.



(a) (b) (c)

Fig. 5. Resultados del algoritmo Q-*learning*. **a**) Evolución de la recompensa media por episodio. **b**) Evolución de la función $\mathcal{L}$ a minimizar **c**) Acciones tomadas por el agente para una prueba de 200 interacciones.

Para el entrenamiento del agente artificial se aplicó el conocido algoritmo Q-*learning* usando una estrategia de exploración $\epsilon - greedy$, con un decaimiento de ϵ con el transcurso de los episodios desde $\epsilon = 1$ hasta un valor mínimo $\epsilon = 0.01$. La tasa de aprendizaje usada es $\alpha = 0.1$ y el factor de descuento es $\gamma = 0.9$. Los resultados obtenidos se muestran en la Fig. 5. La Fig. 5a muestra la recompensa promedio obtenida por el agente durante 1000 episodios de entrenamiento. Cada episodio contempla 100 instancias de interacción. Como puede verse, el agente logra converger a un valor medio de recompensa a lo largo de los episodios. La Fig. 5b muestra la minimización de la función $\mathcal{L}$ durante los mismos 1000 episodios y por último, la Fig. 5c detalla las acciones escogidas por el agente en una prueba de testeo de 200 interacciones. En conclusión este ejercicio demuestra la factibilidad de integración entre un agente de toma de decisiones autónomo y un gemelo digital creado mediante la arquitectura de integración presentada.

5 Conclusión

En este trabajo se presentó una arquitectura de software para el desarrollo de gemelos digitales mediante la integración del sistema operativo de robots y un simulador de procesos de manufactura flexible. La misma permite la interconexión e interacción entre diferentes componentes (tanto de subsistemas de hardware como de software) que pueden estar presentes en un sistema de fabricación flexible. También, se presentó una metodología sistemática para el desarrollo de un gemelo digital de un sistema de manufactura y su integración con un sistema autónomo de toma de decisiones y de esta manera, queda habilitado un entorno que, conectándose naturalmente a través de ROS con la planta de manufactura real, permitirá realizar optimizaciones con el paradigma de GD presentado. Adicionalmente, se desarrolló un sistema de toma de decisiones autónomo basado en un algoritmo de aprendizaje por refuerzos para el problema de manejo de materiales en piso de planta. En un futuro inmediato se tiene como objetivo ampliar los desarrollos de este trabajo a casos con más componentes de hardware y software para abordar otros casos de estudio en vistas a analizar el desempeño de la arquitectura de software propuesta.

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Data Analytics support for the Integrated Planning of Cutting Orders in Banana Crops harvesting: a case study in Colombia

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Abstract. Given the nature of agricultural activities and the environment that they are managing, it is necessary to develop different plans that integrate available resources and climatic conditions to achieve positive results in the future. In many cases, there are different types of errors such as the use of a selective averaging method that ignores uncontrollable factors negatively impacting your forecasting and planning. In the case of banana crops, the climatic factor has relevant affects the harvest, and poor planning seriously impacts the supply chain since delivery times to countries that do not have the necessary conditions to harvest are very high. As a solution, this work develops the integration of two models, one for forecasting and the other for harvest cutting, which seeks to minimize cost variations and allows the desired synchronization in the process of managing the operation. First, the relevant factors to make a correct prediction was identify including non-controllable variables such as rain and associate it with an autoregressive model, resulting in the relationship between precipitation and the percentage of bananas harvested, then developed a planning model as support to find efficient use of the available resources and determine a harvest schedule that responds to the best possible fulfillment of the company's demand, finding the best results through the optimization of a non-linear mathematical model. The results obtained in this paper generated a prediction with higher reliability and a capable harvest cutting planning model, deep food safety, and following the objectives of the company.

Keywords: Agri-business, Integrated Business Planning, food security

1. Introduction

Numerous studies in nutrition show that a healthy meal always begins with the consumption of at least one fruit a day. Banana is one of the fruits with the highest nutritional content, also it is the most important tropical fruit of the world, there are as more than 200 cultivars existing in countries that grow them. (Pareek, 2016) This is evidenced in that 20% of the world banana production is destined for world trade, which makes it, together with apples, grapes and citrus fruits, the most important set of fruit products marketed in the world. Knowing the value of this fruit, which extends worldwide, there is an interest in knowing the conditions in different aspects that surround or make possible its commercialization at such scales. This involves, the places where it is produced and how they do it; On an economic level, the impacts it can have to be sustainable and how they can transform or influence elements that go beyond the economy. Although, the fruit is present in many places given its nature, Colombia, due to its characteristics at the geographical level, has important advantages, as well as difficulties that can be decisive in the execution of objectives.

Within trade, Colombia is currently the fifth largest exporter of bananas worldwide, after Ecuador, the Philippines, Costa Rica and Guatemala. It is estimated that its fruit production reaches 106,000 tons per year on average (Redaccion caribe, 2018). Colombia has had a relatively long tradition as a net producer and exporter of Cavendish Valery type export bananas although it also grows another type known as Creole banana. Banana agribusiness has developed as a traditional agricultural export chain, generating important foreign exchange for the country, maintaining its position as a net exporter, after coffee and flowers. This generates in the country, 95 million cases a year, with an approximate value of US $ 700 million a year and constitutes 3.0% of total exports and 6.0% of non-traditional ones, participating with 0.4% of GDP ((FINAGRO), 2018)

Banana cultivation, given its natural characteristics or because of the context in which it develops, needs planning that considers several aspects from the land where it will be planted until its commercialization and each stage itself can be a planning situation, where they influence External factors such as transport and the destinations where they are going. This work focuses on a part of the whole process concerning the harvest stage and seeks to design a plan that meets one of the fundamental objectives of any industry, supply-demand synchronization and cost minimization.

We describe our main findings as: (1) we give a geo-spatial analysis for farm banana production, and replaced previous prediction methods for the cutting orders, then (2) we develop a model for optimizing the cutting order for banana production. Finally, (3) all things together make the best of our new proposed problem setting: A Geo-Prescriptive Integrated Planning Optimization Model for Banana crop production. This article is composed of the following sections: In Section 2 we present the literature review about the problem under study; section 3 includes methods and procedures;

section 4 provides experimental/numerical settings; section 5 results and discussions. Finally, we end up with the conclusions of the paper and some future research.

2. Literature review

This paper seeks to solve the problems of synchronization of supply and production adapted to a agriculture specifics case in banana crops. models of demand forecasts and predictions through data analytics that automatically affects production to product cut planning were used, considering the available resources and external factors that can have an impact on the entire chain of activities that make it possible to satisfy demand knowing the importance of in supply chain sustainability (Hazen, Skipper, Ezell, & Boon, 2016) and analysing multiple factors that are related to the moment of making decisions. .

One of the most important factors to bear in mind when analysing agriculture are the climatic changes, which has been of great scientific interest lately, due to the way they impact principally in food security. Between 2007 and 2017, the European Union allocated more than 1500 million euros to more than 250 programs led the Food and Agriculture Organization of the United Nations (FAO) in 60 countries, to address food insecurity and issues of agricultural development related to conflict, migration, environment and the challenges of climate change. and many of the investigations aim to control this in regions of difficult water management, as part of the fulfilment of goal 2 of the Sustainable Development Goals - European Commission: end hunger, achieve food security and improve nutrition and promote sustainable agriculture ((FAO), 2018). Research like (Campbell, 2016) names it as of the major challenges of the 21st century and explains in detail the importance of this branch of science. On the other hand, (Myers, 2017) reviews the main pathways by which climate change may affect our food production and make an interesting analysis of the pathways for impacts of climate change on food systems, food security, and undernutrition.

Banana crops are not unrelated to these factors, especially if they are grown in tropical regions where changing rains become a deciding factor in knowing the exact time of harvest and cultivation. To do this it is very important to determine patterns of rain behavior and its effect on the crop. (De Perez, 2019) demonstrates that the combination of rainfall observations with seasonal forecasts can further change the range of possible outcomes to indicate a greater or lesser risk of food insecurity. (Generoso, 2015) finds for a particular household how the variability of interannual and seasonal rainfall has an impact on food security and (Iizumi & Ramankutty, 2015) analyses how climate might influence crop production, including cropping area (area planted or harvested) and cropping intensity (number of crops grown within a year) and finally (Caicedo Solano et al., 2020) define complete a methodology to minimize waste in agricultural banana production systems to ensure sustainability.

Make Forecasting for agricultural data presents great challenges, especially nowadays with the ever-changing climate. (Srinivasan, Giannikas, Kumar, & Guyot, 2019) pose an interesting question to the problem of crop production planning. They estimated suitability and risk parameters and used them in a mean-variance analysis to calculate the optimal sourcing decision under a data-driven modelling approach. Furthermore, (Majumder & Kumar, 2019) present a good study on how accurate weather forecasts improve the predictions for better crop planning. In their case, they study the effect on adaptive farmers, but the method is still of great value for all types of crops. ((Rebortera & Arnel , 2019) , propose a recurrent neural network- long short-term memory (RNN-LSTM) has been used as a new alternative model in time series (TS) forecasting. They proved their method using a banana harvest data from Philippine's cooperative of producers. To our knowledge, this is the most advanced implementation of new prediction techniques for banana crop harvesting.

By viewing the crop processor from a global processor and comp parts of a supply chain, various authors aim to analyse crops comprehensively (Fuchigami, Severino, Yamanaka, & De Oliviera, 2018) presented a literature review of mixed-integer programming (MIP) applications in the fresh agri-food supply chain (ASC). They show that, because of the strong need to increase the efficiency of the supply chain, the planning models have become of increasing importance to producers and companies. However, none of the articles cited in their document relate to banana crops. Also, (Soto-Silva, Nadal-Roig, & González-Araya, 2016) review some of the literature on operational research models applied to the fresh fruit supply chain. They conclude with an outline of the significant new problems facing the industry like the lack of holistic approaches for the design and management of fresh FSC and give directions for future research. Also, (Villalobos, Soto-Silva, & González-Ara, 2019)- from the same group - presented another review on research directions in technology development to support real-time decisions of fresh produce logistics.

In one of the most relevant studies published for fresh fruit supply chain tactical modelling, ((Ahumada & Villalobos, 2011) presents an integrated tactical planning model for the production and distribution of fresh produce. The main objective of the model is to maximize the revenues of a producer that has some control over the logistics decisions associated with the distribution of the crop. (Le Gal, Mérot, & Moulin, 2010) propose a conceptual framework based on three sub-systems (biophysical, technical, and decisional) interacting within the farm is proposed to guide this process. An important part of agricultural production is to handle risks while appropriately managing costs. (Voldrich, Wieser, & Zufferey, 2019) study how, in the context of a global food supply chain, the combination of processing time and cost (PT&C) with operational risk (ORk) yield a novel integrated

3. Methods and procedures

For the application of this methodology, a company in charge of the harvest and logistics of banana plants was analyzed, which currently like many others, uses a method whose success is based on the experience and predictive capacity of the analysts involved in defining the forecast. At this point the data is not completely analyzed, nor are technological tools used to automate and improve the forecasts made. Instead, the company uses a method were defined as a mechanism based on the calculation of a selective moving average that depends entirely on the analyst's decisions to subjectively define the weeks in which the demands behaved similarly, and based on this, generate a forecast from which the company gives the order to harvest.

The banana supply chain has a complex procedure due to be a perishable food product. To develop the operation along the chain, it is necessary to analyze from the components of the land where it will be sown until the detail of how the packaging and transportations system will be to reach the final clients. The planning process begins by calculating the numbers of clusters to be harvested according to their age (from 8 to 12 weeks), the total banana ratio, and the percentage of short-type fruit. With these forecast values, and the historical data the following elements are calculated:

- Quantity of fruit clusters to be harvested (Rac Cos) for each farm and total, this by adding the forecast of racism harvested by age and each of the farms respectively.

- Premium banana percentage (% Premium), which corresponds to the highest quality fruit, is calculated by complementing the forecast of the percentage of short fruit (% Short).

- The ratio of the short banana is calculated by the product of the percentage of short fruit and the predicted total time. The Premium fruit ratio is the complement concerning the total ratio and that of the short fruit.

- The number of short fruit boxes (short boxes), corresponds to the product of short fruit ratio with the number of clusters to be harvested. In the same way, we proceed to calculate the number of Premium boxes and the total amount of boxes refers to the sum of these two quantities.

- The quantity of cut clusters, refers to the number of clusters that were collected (if they are previous weeks) or predicted (if it is the following week) in the corresponding week.

- The clusters harvested by tape and pocketed by age, refers to the harvests by age of specific land, where week 12 corresponds to the forecast of clusters to be cut with this age of this week. So that the numbers 8 to 13 correspond to the age of the fruit. Following this logic, the value for 11 corresponds to an approximation of the amount of fruit cut with this age in the previous week (week 31), that of 10 to the approximate age of the previous 2 weeks (week

30), so on. Therefore, the total corresponds to the approximation of what is harvested by a plantation that began the ripening cycle 12 weeks ago (week 20).

- The values of week x (week 8, week 9, …, week 13), correspond to the percentages of the harvested (if they are previous weeks) or forecast (if it is a subsequent week) in the corresponding week. Calculated by the reason of real packing (Emb Real), the number of banana bunches that are demanded from the farm, and the value of bunches cut by age. The recovery is the estimate of the percentage of demand covered by the plantations that began to mature 12 weeks ago.

- The year and week of packaging (Year Emb and Sem Emb) refer to the calendar year and week of the period.

- The year and week of harvest (Year Emb and Sem Emb) refer to the year and week relative to which the harvesting began, with a lag of 11 weeks concerning the calendar week.

- The abbreviation "Has" refers to the size of each farm in hectares and Bell/ha is the yield of fruit clusters per hectare, calculated as the ratio between the actual packaging and the size of the farm.

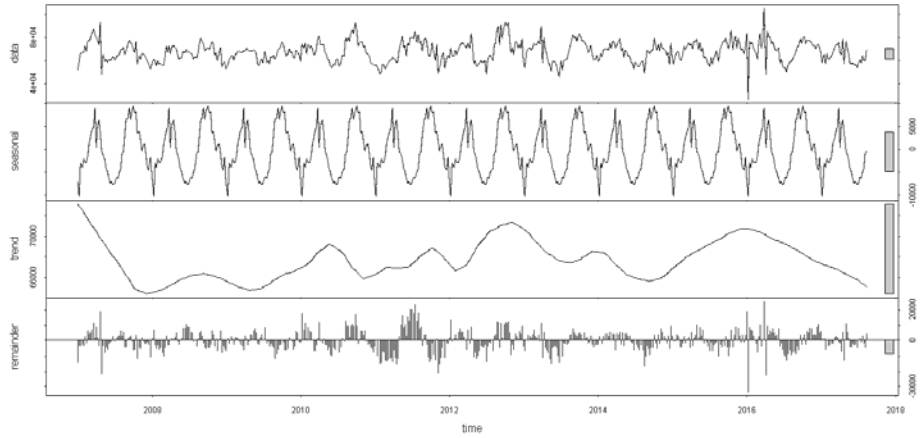
For the beginning of the design process, information on the behavior that the system and its results with the current methods implemented were gathered with real data of what has been its sales, demand, and the costs that having been incurred, principally the operational costs specifically in the harvest, this was obtained to perform the analyzes and made the design process of each section validating with data the fulfillment of objectives by the general design. It should be noted that due to the industry in which the company develops, it is divided into groups of farms for production, some of them own and others that respond to suppliers or subcontractors. For the purposes of the study, this research was done with a small group of farms of the company and the one that has the greatest contribution in terms of production. This paper proposes an integrated planning optimization model which is a process to better match a manufacturer's offer with demand by better planning the operations to create a single production plan. The broadest objective is to obtain an integrated vision of planning by extending the forecasting process to sales, marketing, finance, and operation for its contribution and collective adjustments.

4. Results and Discussion

To carry out the statistical analysis of the behavior of the harvests, weekly harvest data were analyzed over 10 years between 2008 and 2018, the graph below was developed with information of the harvest and made through the software R initially shows the

natural behavior, then what would be its seasonal behavior, its trend and finally the behavior of errors based on the behavior of the trend, showing that there is no constant trend in this process, but a seasonality in the series

Fig. 1. Decomposition of the time series for banana crop harvested



4.1 Forecasting Methods

we propose to find the relationship for the inclusion of rainfall in the forecast through a correlation model. The sectors included were defined when presenting rainfall data. Next, the correlation model for each sector will be calculated and the data is fed to the optimization model. Generated a relationship factor through the correlation coefficient between rainfall and cutting percentage. In this way, the Spearman correlation coefficient for each sector was calculated. Also, in order to define the percentage of fruit that will be cut with respect to the forecast, the average rainfall per sector is needed, the formula to define the percentage of what will really be cut considering the rains are:

$$\%\ Cut\ with\ rainfall\ _{i,t} = 1 + \left(\frac{(Correlation\ coefficient_i\ , * rainfall\ precipitation\ _t)}{average\ rainfall\ of\ the\ sector_i}\right)$$

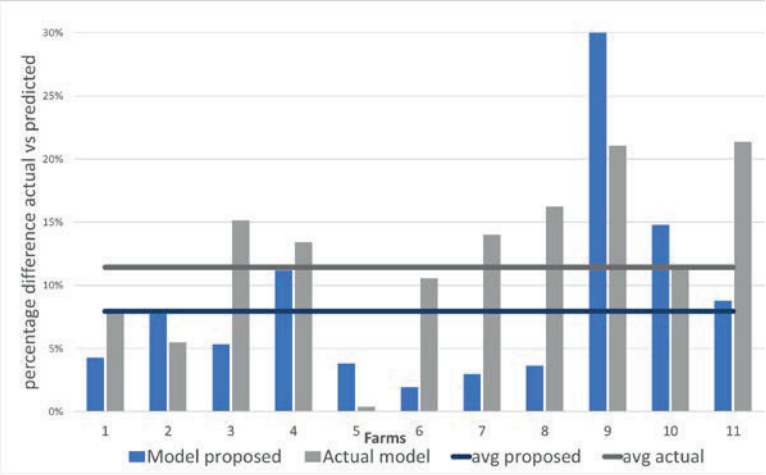
Where i is the sets of possible locations and t is the sets of the weeks of a year. However, the sensitivity of each sector to rains must be taken into account, that is, the higher the average rainfall in a specific sector, it means that both farms and crops located there are more accustomed to rainfall compared to others that have a lower average, therefore it is likely that the cutoff percentage is less susceptible to the rainfall generated. In this way, the higher the average rainfall value in the sector, the percentage of cut is less sensitive to rainfall and therefore increases. From this formulation the

adjustment to the forecast is made by multiplying the percentage of cut including the rains with it.

The R-project software tool was used using time series analysis particularly the ARIMA model due to the seasonal characteristics of the data, which were repeated every year or 52 weeks. For reducing the bias on the forecast the average error was calculated training the model with the forecasts for week 2 harvest until week 31. With the mean error (ME) calculated, a forecast correction was made with the subtraction of the ME and a fixed value. To carry out the correction test, the correction was predicted and applied for the weeks of 32 from a year to week 9 of the next year, this analysis was done for all farms, and for all types of fruit, the adjustment of the forecast given by the ARIMA models, through the ME results in the reliability of 99.426%. This reliability is superior to that resulting without the adjustment of ME 98,724% and that of the current process 99,059%. That is, an improvement is made with respect to the current model at 0.367%.

Figure number 2 is observed the percentage difference related to the quantity of real cut banana and the forecast using the current and the proposed model, out of the 11 cases analyzed, 9 won the proposed model with an average approach of 6% when the current one had 12%. In general, the model proposed using the correlation coefficient shows improvements of 6% compared to the current one used. This impact could also be associated with food security, since a better approach to reality can cut the fruit in the exact moment to be transported.

Fig. 2. Percentage difference related to the quantity of real cut banana and the forecast using the current model and the one proposed in 11 farms



Once important elements of the system were identified, their current status and the harvest was forecast, a mathematical model was designed to plan the cut based on the

search for the lowest operating cost and considering the restrictions associated with the operation.

4.2 Mathematical Formulation of harvest cutting plan

In what follows, the integrated production planning model follows.

Indices for the model:

- *t:* index that identifies days of the week for cutting, $t = 1, ..., 7$

The variables used for the model

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- *Xt*: Clusters to be cut in week
- M_t: Clusters to cut day *l*, in week *i* of the farm *f*
- H_t : Cutting clearances in week *i* of day *l* of the farm *f*

System Parameters

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- *D:* Demand to replace in the week considering the rains
- *R:* number of clusters that can cut a person
- *r*: ratio of farm cluster by box
- *A*: capacity of clusters in the farm
- O_t: designation of cut for day *l* E (0,1). at least one must have the value of 1 and least one must have the value of cero for transport
- P_t: people required for the *l* day of the week *i*
- *Cw*: cost by worked required
- *Cm*: aggregated cost by produced box
- *M*: dummy variable cost

Objective function

.

$$\text{Zmin} = \sum_t \left(\left(\frac{M_t}{R} + 4 \right) * O_t \right) * \text{Cw} + \sum_t \left(\frac{M_t}{r} * O_t \right) * \text{Cm} + \sum_t H_t * M \quad (1)$$

Constraints

$$\sum_t M_t * O_t + \sum_t H_t * O_t = D \quad (2)$$

$$\frac{\sum_t M_t * O_t}{R} \leq A \quad (3)$$

$$\sum_t (M_t * O_t) = X \qquad (4)$$

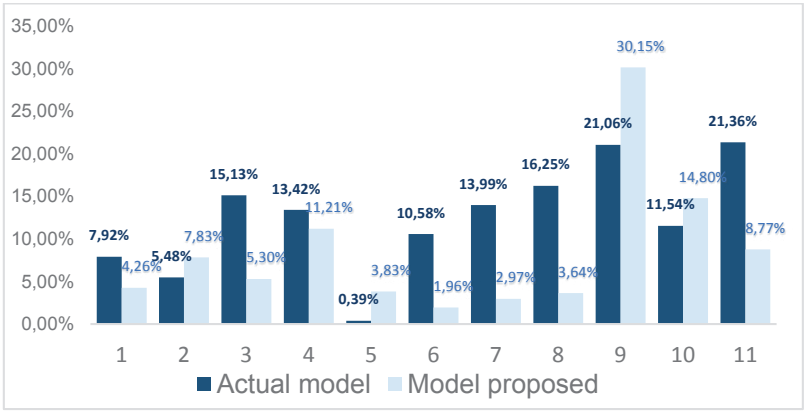
$$M_t = \frac{X}{\sum_t O_t} * O_t \quad \forall\, t \qquad (5)$$

$$M_t, X \geq 0 \quad \forall\, t \qquad (6)$$

Equation (1) represents the objective function within it containing 3 summations associated with each cost; The first of these is related to labor costs, the second is associated with the costs of materials required and the last one takes into account the costs required to meet demand. Within the constraint equation (2) is associated with meeting demand, equation (3) has to do with meeting the capacity of bananas cut on a farm, equation (4) is used to calculate the total value cut in one week and equation (5) is associated with balancing the cuts per day, that is, every day that can be cut, the same amount is cut. Finally, equation (6) is the equation related to non-negativity. This optimization model seeks to reduce operation costs to the maximum by considering weekly demands. The idea is that this model be replicated in each farm for each type of banana and in each week and thus ensure the optimal way to make the cuts considering the demand forecast above

Comparing the model to the one used before in 11 farms in a period, it is observed that the precision (different between real and model) of the cut order generated through the planning model and methodology used in the project is 91.39% while the precision of the current cut order model generated is 87.54%. In this way observed that with the proposed method a better cutting order is 3.85% more precise than that generated by the company.

Fig. 3. Comparison of both cutting orders with respect to the actual cost



Using the method proposed including the rainfall correlation factor the company could have to buy 2594 bunches less than using the normal methods, this means spent less on buying bunches to cover the demand due to the increase in the accuracy of the generated order. On the other hand, to evaluate the impact that the inclusion of the precipitation factor has and the quality of the calculated ratio factor in the generated prediction, rainfall is shown as well as the comparison of cut orders generated with and without rains. Considering a total real packing of this week, this is 79013 bunches, in this way it is determined that the inclusion of rainfall in the model improves the accuracy of the cutting order by 0.475% taking as reference the total real packing.

Impact of rain consideration		**Precision**
Total to be cut (excluding rains)	79688,22849	99,146%
Total to be cut (considering the rains)	79312,36128	99,622%

Table 1. Comparison of cutting order with and without rains

5. Conclusions and future research

The use of formal methods, the inclusion, and considerations of uncontrollable factors and the evaluation of their impacts, as well as the correct identification of restrictions and changes of the system, allow designing a mathematical model suitable not only to minimize costs but can synchronize the best possible supply-demand relations, general objective to which this project responds successfully. With the improvement of the forecast and delivery of prediction, the planning process undergoes an improvement. From a forecast with better reliability, a more accurate cut order is generated.

The use of computer tools (R-project) for the generation of forecasting models allows better accuracy when forecasting, compared to the current intuitive forecasting model. Obtaining a comparative improvement of 0.367% of confidentiality in the long term in our forecasts. The inclusion of the factor of rain in the prediction model makes that the forecast is closer to the real, in this way the veracity of the ratio factor between the rains and the cut percentage is validated and also an improvement in accuracy of 0.475% in the forecast is established final for the cut order. The cultivation and harvesting models are integrated through a set, which expresses a production system that must be fully optimized, resulting in the reduction of production costs due to the overproduction of waste, quality, workers, raw material, and machinery, among others. One of the most relevant contributions of this work was the implementation of mathematical models, which, as in this work is focused on profit in the cutting processes, can be focused on optimizing the safety and control of the operation and also apply it in other activities as irrigation or sowing processes. Collecting the information of each one of the factors was one of the most important barriers to this work, the low access to effective telecommunications make it impossible to communicate and access IoT media that facilitate monitoring and control tasks and allow and implement 4.0

technologies in the agricultural industry giving the possibility to automate different tasks, improving food safety and profits.

Future work must include fruit transportation and the choice of the appropriate transportation system. We have been dealing with different types of equipment configuration for improvements on the transport of fruit, such as the use of 45" reefer containers, bi-train trailers, smaller batch trucks, and more.

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A proposal Roadmap to implement Industry 4.0 in SMEs

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Abstract. Small and medium-sized enterprises (SMEs) represent a large portion of the economy and the availability of countries' jobs. These organizations, compared to large ones, have some advantages such as the faster response to changes and adoption of new systems and new technologies, as well as some limiting factors, such as financial capacity to investments, and reduced human resources to perform all necessary tasks. With the advent of the so-called Fourth Industrial Revolution, new technologies emerge, with its multiple trends in applications and integration of physical and cyber systems, leading to new production strategies necessary for companies to position and competitive advantage in the long-term market. The great challenge for organizations, especially for SMEs, is to perceive and understand quickly, appropriately and assertively, the movement of abrupt changes resulting from these trends of convergence of technologies and systems, which requires training and guidance for the people involved in the process to implement Industry 4.0. The present work proposes a Roadmap for the implementation of Industry 4.0 for SMEs, based on the concept of Lean Thinking. It is intended to present a new perspective through a guideline that supports and allows decision makers to better understand the process to adopt the digital transformation in their SMEs organizations.

Keywords: Industry 4.0, SME, Roadmap, Lean Six Sigma.

1 Introduction

In order to improve production, from the mid-eighteenth century, man experienced three Industrial Revolutions: (1) mechanization at the end of the 18th century, (2) electrification in the early twentieth century and (3) Computing in the early 1970s [24][36]. In the early of XXI century there is the movement towards the Fourth Industrial Revolution, theme presented in 2011 Hannover - Germany, and which has been denominated in different ways in each country, relating to its programs of innovation and technological integration of manufacturing.

This Fourth Industrial Revolution is comprehensive, being defined in several ways by authors in the literature, still without a consensus of a standard description, but which basically synthesizes and refers to the integration and convergence of current technologies manufacturing field [16]. The name that gained greater prominence and popularity to refer the Fourth industrial revolution was the originally presented in the Germany in

2011: "Industrie 4.0" or "Industry 4.0" [4] [10]. In this digital revolution technologies are present simultaneously, both in the various personal devices such as smartphones, tablets, smart products, etc., as well as in industrial control and automation equipment.

Due to its scale, scope and complexity, this industrial transformation is already different from everything humanity has experienced so far [31]. The process requires from people and organizations, greater perception, understanding and preparation to be able to deal with the digital technologies that come up every day, and that generate other new technologies constantly [14]. In this context are small, medium and large organizations, which are all challenged to keep up with the changes brought by the digital transformation of Industry 4.0, so that they stay in the market and do not run the risk of succumbing quickly by not updated. Large companies have greater resources to meet these challenges, but however, small and medium-sized enterprises have several limitations that hinder, delay and prevent the implementation of Industry 4.0.

The SMEs plays a key role in the world economy, and even if their classification changes according to each country, depending on the number of employees they employ, as well as the value of their gross revenues. Such kind of company represents a large portion of national economies, in various sectors with industry, trade, services, agriculture, among others. The great challenge to the SMEs, lies in understanding this movement and digital transformation, and simultaneously overcoming its internal barriers of limited resources - financial, human resources, knowledge in new technologies - to adopt and implement the concept of Industry 4.0.

This scenario leads to the following problem to be explored in this work: "How to support Small and Medium-sized Enterprises (SMEs) so that they can implement the concept of Industry 4.0?". Our proposal is, based on the latest published scientific papers on the subject, to propose a Roadmap that allows SMEs to implement the concept of Industry 4.0 directed to their reality. This proposed guideline will be based on Lean Thinking combined with multiple perspectives of people management, organizational change and digital maturity of SMEs, allowing discovered knowledge to be adopted by professionals from various sectors.

2 Industry 4.0: Technologies, People and Organizations

A "revolution" alludes to an abrupt and radical change, which in history began with agriculture and domestication of animals, moved to the production, transport, urbanization and arrived in industrialization [31].

We understand that the great differential between the four revolutions, is that the first three originally occurred within the factories, and then set out to be adopted by the whole society. The movement started from industrial steam-powered machines to trains, from the electrified lines production, to daily life of homes and commerce, and finally, from the large central computers "Mainframes" and industrial automation controllers, to personal computers [27][33]. In this new context of industry 4.0, technologies, people and organizations will be fully integrated into a complex physical cybernetic

system, which will need to meet new technological, human and organizational requirements, as well as face and overcome barriers and challenges.

2.1 Enabling digital technologies

The integration of cyber-physical systems (CPS) unite the real and virtual worlds, through the various digital technologies present today in our daily lives like: 3D Printing, Virtual Reality and Increased, Big Data, Data and Process mining, Artificial Intelligence, Machine Learning, Mobility, Cloud Computing, Gemini and Digital Shadow, Internet of Things, Collaborative Robots, and smart concept in Factory, Products and Cities, among others [1] [11] [12] [14] [35].

The Industry 4.0 are guided by principles as interoperability, real-time decision making, decentralization, virtualization, modularity and service guidance. The expected benefits and results are the improvements of production processes, greater human-machine-machine interaction, ubiquity of information. Also, increased safety and reliability, resource optimization, cost reduction and waste, large-scale personalization and technological innovation [4] [9]. Therefore, the transformations brought by digital technologies take people in a new direction in which the development of new capabilities and skills will be necessary.

2.2 People

The development of human skills and capacities is fundamental for the implementation of Industry 4.0. It is important to consider techno-social aspects like knowledge in technology information and new technologies, information analysis, organizational and business understanding. Also, must be consider the ability to work and interact with modern interfaces and media, integration of different processes, management and transfer of knowledge, networking, communication, linguistic skills, teamwork and self-management [8] [36].

Studies on the subject, for the most part, however, still address more the technical aspects of technologies relevant to Industry 4.0, than the management issues and organizational culture. The effort is so that there is a balance of skills simultaneously in the fields of technical, social, personal and methodological knowledge, conflict resolution, decision-making, adding values. In this context it is important consider the norms, beliefs, attitudes such as how the activities are performed, the way people behave, their flexibility, change tolerance, leadership, motivation to learn, commitment and cooperation, ability to work under pressure, thinking about sustainability and ethics [8] [21].

Human Resources Development (HRD) will be important in this context to define the technical-social role of people within the new processes. This can be done through a systematic approach evaluating people´s maturity levels with appropriate tools and support them in order to reduce the level of inhibition and support the process of change, by a transparent and open communication culture [27].

Professional Management includes studies with proposals for HR-oriented life cycles, which consider planning, attraction, recruitment, support, skills areas, retention and output of a system employee. After that, a new cycle starts with a new planning [28] and where the new requirement for Leadership 4.0 is defined as well [26]. It seems that

the fourth industrial revolution is only at a very early stage, not yet fully understood by people, what will affects on society, organizations and individuals. Also, how companies will deal with a paradox between be open and adaptable to external effects and simultaneously how to keep knowledge and intellectual property internally [28].

2.3 Organizations

Because people´s personality is unique and individual, their combinations when grouped, build organizations also unique which makes the entire system very complex and dynamic. Traditional hierarchical models of shop floor, office and peripheral departments of logistics, inventory and support; do not fit the new concept of the fourth industrial revolution [24].

The new industry presents an autonomous and intelligent manufacturing model, where physical and cyber systems interact instantly in a collaborative work, controlling and monitoring the entire process without human intervention. This new configuration will be supported by an information technology infrastructure and Communication, digital modeling, data collection, storage and processing advanced system [36].

What is required here is a long-term transformation of our global perception of industrial production through the perfect connection of the digital and real worlds. The principles of this new factory design are modularity, decentralization, virtualization, service guidance and real-time capacity and interoperability [1] [11] [13]. This new manufacturing configuration is a four-dimensional physical-cybernetic system: the factory and smart products composing the real physical world; and data-oriented operations and services, these in turn, composing the virtual world [14] [17].

Interoperability functions as a catalyst, as it allows continuous communication between machines and systems, in open standards with flexible interfaces, providing a layer where everything works in an integrated way - information, services and processes. Some authors include other perspectives like, economic, technological and social [5] [9], which makes the whole process of implanting Industry 4.0 challenging with many barriers to be overcome.

2.4 The requirements, challenges and barriers to Industry 4.0

The challenges and barriers to be transposed into the implementation of Industry 4.0 are multifaceted and related to cultural factors of people and organizations, technology and innovation, infrastructure, workforce qualification, communication. Additionally, must be considered factors related to economy, jurisdiction, policy, environmental, social, accelerated pace of new technologies and difficulty understanding and absorption of the theme because it is still very incipient [30][33].

The main feature of the Fourth Industrial Revolution is real-time decision making and response, and following in this sense, companies should be agile to develop in an environment still uncertain and turbulent. They should perceive changes in a competitive environment, with immediate demands from integrated platforms and data-based business models [18].

The Implementation of the innovative project of Industry 4.0 is a challenging process that requires a long-term plan – the so-called Roadmap or Technological Roadmaps.

Such kind of plan will evaluate internal (vertical) and external (horizontal) scenarios of organizations, under the strategic perspective, considering existing technologies and experiences, combined with the research of new solutions and markets [9]. In more elaborate long-term plans, are considered in Roadmaps the vertical and horizontal perspectives of integration in the value chain, the product and project lifecycle, personnel infrastructure and the development of new associated technologies [4].

In this respect, a recent study [29] proposes the introduction of a methodology using multicriteria decision analysis (MCDM/A), which allows the evaluation of local and legacy systems for the implementation of projects related to Industry 4.0. The methodology consists in six stages: (1) Process Evaluation, (2) Project Definition, (3) Evaluation of Local Systems, (4) Evaluation of Legacy Systems, (5) Choice of the best solution and (6) Final decision making. Therefore, the Roadmaps for the implementation of Industry 4.0 must consider the socio-technical aspects, from the training of people, the assessment and preparation of organizations regarding the processes of change, in the context of new technologies brought about by digital transformation.

3 Small and Medium Enterprises into Industry 4.0 context

SMEs need special support in the process of implementing Industry 4.0, due to their specific limitations in understanding the digital transformation movement, their internal barriers of limited financial and human resources, and acquisition of knowledge in new technologies, which must be overcome. SMEs have specific management and business models that should be considered in the process of implementing industry 4.0. In a recent study Moeuf et al. [20] highlight that such kind of companies are not directed to the transformation of your business model, since they are not yet as well equipped, and prepared to implement Industry 4.0.

According to this study, SME´s initiatives still are cost-oriented, exploring IoT and Cloud Computing technologies, only for tasks of monitoring of production, and improving the capabilities and flexibility of current processes. Also, SMEs have an analytical structure composed by: (1) Industrial performance objectives; (2) Management capabilities of industrial processes and (3) Means for the realization of Industry 4.0 for its technologies [20].

According to Müller et al. [23], the business models of SMEs should consider three points: (1) Value Creation, (2) Value Capture and (3) Value offer; and the main issues are how such companies perceive and understand the phenomenon of Industry 4.0. The authors also highlight how SMEs can innovate their business models as a result of this transformation movement into the dimensions of process digitization, intelligent manufacturing and connectivity between companies. Finally, the study encourages SMEs managers to explore other forms of innovation in their business models, with customer orientation and not to the product, search for new methods of payment by customers and individual adaptation to each customer, that is, customization.

The difficulties encountered by The SMEs to implement Industry 4.0, according to Sevinç et al. [32], reside in four main areas: 1) Innovation relative advantage, complexity, relevance, relationship and Intelligibility, 2) Organization to support of high

management, organizational size and specialization of the IT area, 3) Environment the competitive pressure, external support and distrust of the real benefits and 4) Costs related to the transition, maintenance, technical support and training. Within this context, the Lean Thinking and Six Sigma concept can be applied into the Roadmap to provide an underlying support base for SMEs to implement Industry 4.0.

3.1 Lean Thinking and Six Sigma (LSS)

The Lean Thinking was developed from the Toyota Production System (TPS)[37] and Six Sigma was developed at Motorola in the mid-1980s [34]. In general terms both concepts are focused in improve process efficiency, eliminate causes of defects or errors, eliminate of losses and waste, and resources optimization, which are fully adherent to Industry 4.0 philosophy.

For this reason, both concepts can provide an underlying foundation and can be applied in the digital transformation implementation. Important to remark that the application of those methods can be alone or combined and depends on the field and degree of the problem to be evaluated and the problem which is intended to be solved [2] [34]. In a recent study Moya et al. [22], highlights 5 hierarchical groups of critical success factors for SMEs to implement Lean Six Sigma:(1) External relations, (2) HR management; (3) Project Management; (4) Strategies and (5) Process Management.

According to Müller et al. [23] SMEs tend to view Industry 4.0's new business models with caution due to their resource limitations and specific difficulties, and therefore require differentiated and adapted solutions. According to Sevinç et al. [32], SMEs have greater difficulties with their own organizational structure and costs to implement Industry 4.0 and less difficulty in understanding the issues of the environment and innovation.

Antony et al. [3] proposes two questions should be asked for a Lean and Six Sigma application approach: "(1) Is the solution known or unknown? and (2) Is the root cause of the problem believed to be in a value aggregation step in the process, or in the links between the value addition steps?". Both questions must be considered during maturity analysis and implementation of Industry 4.0 from technology, people and organizational changes point of view.

3.2 Digital Maturity

In his study, Mittal et al. [19], points out that Strategies of SMEs often depend on the owner, leader or manager, and the adoption of Industry 4.0 depends on their understanding of the theme, and its willingness to proceed with the necessary change. As barriers relevant to digital maturity, it highlights the resistance to the adoption of advanced technologies and digitization, the high training of employees, the highly centralized processes, non-compliance with technological norms and protection of intellectual property rights. Related to the dimensions of digital maturity, the author highlights: Strategy, Leadership, Customers, Products, Operations, Culture, People, Governance and Technology. As a great highlight the authors note that there are initial technological conditions for each SME, which should be considered in maturity models adapted to this type of organizations.

In a recent study North et al. [25] points out that there are a growing number of maturity models for companies, many of which were developed by consulting firms, are focused on large corporations, and aimed at processes, not training, not being fully suited to small and medium size companies. The level of maturity perceived in this study is moderate and indicates that SMEs are more focused on perceiving the environment, and less about taking advantage of the opportunities offered by Industry 4.0. The maturity evaluation is an important step in the Roadmap for SMEs to do an assessment of their real situation face to digital transformation in order to identify the opportunities to take, needs of knowledge to be acquires and barriers to overcome.

3.3 Strategic Digital Roadmap and Framework

The Roadmap developed by researchers consider different perspectives structured in phases or steps that address in general the creation of an initial common understanding, identifies and evaluates the different scenarios relevant to the organization, prioritizes and prepares the implementation plan [10] [15]. In his study North et al. [25], presents a Framework for SMEs that considers dynamic growth capabilities digitally enabled holistically and oriented, as a proposal to fill a gap for such companies on their self-assessment of digital maturity. The study highlights four main points: (1) Detection of potentials of digital growth; (2) Development of a strategy and mentality for such growth; (3) Digital learning and (4) Resource management for digital transformation.

Ghobakhloo [7] in turn, reviews the ongoing research on Industry 4.0 and seeks to offer a strategic Roadmap, which serves manufacturers and serves as a guide to the digital transition process. This guideline presents six main steps: (1) Strategic Management; (2) Marketing Strategy; (3) Human Resources Strategy; (4) IT Maturity Strategy; (5) Intelligent Factory Strategy and (6) Value chain management strategy. Considering the descriptions in previous section 2 and 3 related to technologies, people, organizations, barriers and difficulties and Lean Six Sigma in the SMEs context, we propose our Roadmap in the next section.

4 The proposed Roadmap model for SMEs 4.0

The digital transformation brought by the fourth industrial revolution has required attention from small, medium and large organizations to update themselves and adapt to this new reality, so that they remain in the market and do not succumb in a short time.

Technologies are increasingly present in the daily lives of people and companies, both in product production and service delivery. The integration of such technologies in the structure of the business model requires perception, analysis, decision making and actions from the managers to monitor this movement. Because it is still an incipient topic, many people do not have a clear view on how to visualize, understand and implement Industry 4.0 in their organizational reality, and for this, a Roadmap becomes a fundamental tool in this process.

As for large organizations, many of them already have maturity and a plan to implement Industry 4.0, some of them are at the forefront as forerunners in the subject, they are large, have more resources and structure to take the lead in the adoption of Industry

4.0. However, most global companies are small and medium-sized, where resources and structure are limited and scarce. These limitations are a huge barrier for such categories of organizations to also adopt the context of digital transformation.

One of the most challenges for SMEs lies in the fact that they are at a beginning where they do not even fully perceive and understand the concept and importance of Industry 4.0 in their business models, and precisely because they are not understand, run the risk of ignoring and neglecting and to succumbing in a short time. In this context, this research aims to fill a gap of knowledge, proposing a Roadmap applicable to small and medium-sized enterprises, so that they can perceive, visualize, understand, adopt and implement Industry 4.0. Therefore, SMEs will have support from that tool from its strategic planning to its operational processes.

During the development of this work, papers were consulted that address different points of Industry 4.0: global overview and trends of Industry 4.0 [13] [16] [24], enabling digital technologies [5] [12] [35], people management issues [28] and leadership 4.0 [26], organizations change factors [18] [21], maturity digital analysis [1] [11] [19] [25]. Also was found considerations related to requirements [17], challenges [30], success factors and barriers [33] related to Industry 4.0, the SMEs inside this context and also into Lean Six Sigma concept [20] [22] [23] [32]. Also, other issues were addressed like the Roadmap for the implementation of Industry 4.0, from the perspective of the organization and technologies [4] [6] [10], standardization [15], and the necessary human resources skills [8].

Those studies show that organizations develop their business plans considering the strategic, management, culture and people perspectives. They highlight the data generated by their most diverse systems and equipment, seeking to discover patterns and knowledge so that decision-making in its operations is aligned with their business models and strategic plans [18]. Those work, also address the perspective of organizations and enabling digital technologies, their areas of knowledge, the guiding principles of this industrial revolution. Are mentioned also the strategies, investments, infrastructure and physical-digital systems, maturity analysis and implementation of Roadmap with analysis of benefits, capacities and filling of knowledge gaps [4] [6] [10].

Taking all considerations above, we propose a Roadmap according to Figure 1.



Figure 1. Roadmap. (Source: prepared by the authors)

This guideline addresses six main steps as described below:

1) **Vision** – The necessary work of raising awareness of managers and decision makers in SMEs related to Industry 4.0, its strategic importance for their organizations in the short, medium and long term. At this stage the objective is to detect the primary needs for organizations, sensitize managers so that there is an initial understanding and alignment within the context of digital transformation and its technologies.

2) **Strategy** – At this stage the organization will evaluate its strategic positioning considering the internal and external environments, its business model, its vision of the objectives and goals to be achieved, or even altered in the face of the new reality that Industry 4.0 offers. As well as the definition of expected results, identification of new opportunities that can be taken advantage, also barriers and challenges to be overcome.

3) **Organization** – At this stage, managers need to self-evaluate their current conditions and future needs to implement Industry 4.0. On this phase are considered: organizational structures, IT infrastructure, R&D development, their processes, the knowledge needed to monitor this new industrial revolution, mainly current human resources, their skills and capabilities, the needs of new training and the gaps that should be filled.

4) **Analysis** – This important step will be dedicated to an evaluation of the organization's maturity in Industry 4.0: where the company is located, where it intends to be in a soon future, what it will need to do and what it will need to change to achieve its goals. Here are all the steps discussed above, to support decision-making regarding the selection, prioritization and evaluation of projects and objectives to be achieved.

5) **Planning** – It will be dedicated to the issues of available resources and the new one necessary, the standards to be followed, the procedures and methods that will compose the work plan for the implementation of lean six sigma concepts and Industry 4.0.

6) **Development** – It will cover the implementation of a short-term, high-impact pilot project that delivers visible and consistent results for an assessment of the effectiveness of the workplan, with the necessary adjustments for its definitive implementation of Industry 4.0.

5 Conclusions

SMEs face challenges and barriers for the implementation of Industry 4.0 to a higher degree than large organizations, due to their major limitations on lack of resources, support and access to technological knowledge and methodologies, as well as to people management issues and organizational changes.

Therefore, for the implementation of lean thinking concepts and Industry 4.0 for SMEs, a Roadmap is an important tool that can shorten and facilitate such a process, where they are considered the critical success factors related to technology, culture, politics, social, environment and financial.

We understand that the Roadmap proposed in this work will serve as a practical guide where technical, social and strategic aspects of SMEs are considered. Such guideline offers an underlying basis for decision makers to understand, assimilate and adopt the concept of Industry 4.0 effectively, and thus overcome barriers and challenges, take advantage of the benefits brought by transformation digital.

Our perception when developing the present work was that in the consulted studies, the authors focus and deepen aspects related to digital transformation from technical, organizational or social point of view, but not combined in a guidance to fully support SMEs. Therefore, we decided to gather and address in the proposed Roadmap, considering the combination of Technology People and Organization in order to offer a guide which can support and contribute to SMEs in the Industry 4.0 implementation.

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Digital transformation framework for adequacy of maintenance systems to Industry 4.0

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Abstract. Manufacturing execution concepts at the highest level of automation and interoperability are proposed by Industry 4.0. This is thanks to a group of information and communication technologies capable of creating integrated and connected systems, known as – cyber-physical systems. This network of integrated systems has been promoting gains in productivity, altering the profile of the workforce and the very conception of the work that will have more cognitive demands, increasing competitive potential. Therefore, organizations are more than ever willing to adapt for this scenario. Aiming to facilitate this digital transformation, avoiding an inefficient allocation of financial and human resources, the present work proposes a framework that provides the necessary guidelines for such a transformation becomes viable. This will be done by a series of analysis using multicriteria decision making methods (MCDM), evaluating the maturity of legacy systems, with a focus in the field of industrial maintenance. Those analysis are also based on the RAMI4.0 architecture, Total Productive Maintenance (TPM), Framework for Enterprise Interoperability (FEI), and will provide companies with guidelines for adequacy plans. To test and validate this framework, a multinational industrial entity belonging to the automotive sector was selected as a case study. The application results confirm that such tool can help in digital transformation projects and indicates adjustments for this to be done in a better way.

Keywords: Industry 4.0, Industrial Maintenance, Multicriteria Decision-Making Methods (MCDM), Interoperability, Digital Transformation.

1 Introduction

In the midst of a highly informational scenario, interoperability is an element to be measured by organizations. Such term represents the capacity of a system to communicate between two or more others, in order to use the shared data and access external functionalities [1]. Among the technologies that seek to consume interoperability in manufacturing, the Internet of Things (IoT), Big Data, Artificial

Intelligence (AI), 3D-Printing, Augmented Reality, Machine to Machine (M2M), Analytics and Cloud Computing stand out. Classified as information and communication technologies (ICTs), they are the basis for Industry 4.0 (I4.0), enabling the emergence of cyber-physical systems. According to [2], some of the benefits that such systems' network have provided to organizations are: increased productivity, alteration of the workforce profile and increased competitive potential. However, for the implementation of those technologies to be assertive, it is necessary that conceptual, technological and organizational requirements are satisfied. As the world experience a time of transition to I4.0, this adaptation recurrently involves legacy systems that [3] characterize as those with high usage times, which are vital to the organization's business, and does not fit into future IT strategies.

Notwithstanding, modernization is not easily prioritized by organization, similarly for the maintenance sector, which is seen more as an inevitable necessity than as a goal to pursue. However, the role of industrial maintenance has become a strategic element to achieve business objectives [4]. To [5] the maintenance goals involve: Safety, expressed through a higher reliability coefficient of equipment prone to critical failures; Availability when considering the time when the equipment is producing at full capacity; Budget, involving the reduction of maintenance costs. Those goas are easily related to the benefits provided by I4.0.

Given the difficulty evidenced by digital transformation initiatives for legacy systems and the expressed close relation between maintenance and modernization goals, the research developed here sought to answer the following research question: "How to define a technology prioritization plan, in the field of industrial maintenance, in order to adapt legacy systems for Industry 4.0 requirements?". Therefore, focusing on the industrial maintenance area and based on an assessment of qualifying attributes of a given organization, this work seeks to establish a digital transformation framework with a set of models based on Multicriteria Decision Making Methods. Our hypothesis suggests that such tool will make it possible to elaborate more assertive guidelines, capable of aligning legacy maintenance systems with the vision of a highly interoperable manufacture, necessary to fully access the benefits brought by Industry 4.0.

2 Theorical Dimensions and Scientific Scenario

The disruptive technologies envisioned for I4.0 promotes to escalate industrial productivity, putting current economic models in check, foster the growth of industrial organizations, changing the profile of the workforce and ultimately increase the competitiveness of companies [2]. Thus, the proximity with the term "interoperability" is evident because of the prominence of such technologies, which will increase the collaboration between systems, machines and people; that way, enabling greater speed, flexibility and efficiency in production processes, resulting in higher quality at reduced costs. The researches presented here will show how those gains can be achieved in the maintenance sector, before exploring others horizons.

Nonetheless, implementing a system with the maturity level necessary to operate in the Industry 4.0 bias will require a digital transformation project. With this in mind, and understanding that every project must operate with a budget, or maximum expenditure's cost, the present work explores a premise that "not everything which is wanted to be implemented (e.g., maintenance functions of a I4.0 system), can actually be implemented".

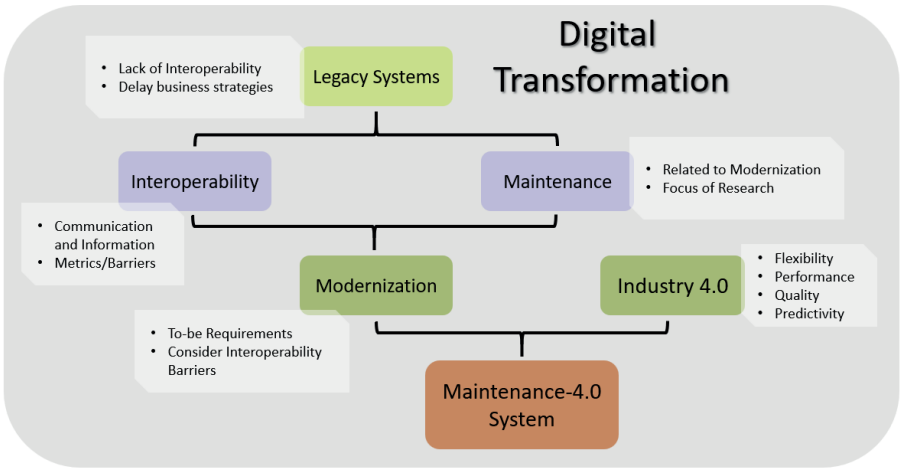

Fig. 1. Research elements.

Considering the Fig. 1 elements overview, the researches in this work explores how to adequate maintenance legacy systems requirements for the I4.0 scenario. By hypothesizes, the technologies suggested for implementation will increase the maturity of a systems considering interoperability barriers, i.e. without harming subjacent systems in the process of implementing those technologies.

2.1 Legacy Systems

Even after three decades of research in modernizing legacy systems, it is notable that many remain in operation. This is due to the fact that these systems are generally very comprehensive [6, 7]. They interoperate with other processes or subsystems, only remain in operation due to their technical complexity of replacement and/or adaptation and criticality in the organization's operations, in such a way that remain in constant activity. Every system is likely to become legacy at some point and its data is characterized as valuable, since its history can be used to understand its behavior in search of optimization [3]. However, to remain competitive, companies must continually change their processes, sometimes radically, and legacy systems can delay modernization processes and directly influence the company's business strategy [8].

2.2 Maintenance-4.0 Technologies

The legacy systems scenario researched for this particular work was constrained to the industrial maintenance, a sector easily impacted by I4.0. With an exploratory character,

a literature review was focused on the Industry 4.0 base technologies that are relevant to the maintenance sector. Here, three research rounds were carried out.

First round. A first research round was sought to understand a general context of I4.0 technologies, and for that, reports with frameworks already formalized in the literature were used. The objective was to gain an overview of I4.0 technologies, in the view of different technology consultants, which were [2, 9–18].

Second round. In the second round, the results from the overviewed technologies where validated in academic articles, focusing on solutions for the maintenance sector. This research round was conducted as follow: (i) was searched the relation between "technology" AND "maintenance" (e.g., Cloud AND Maintenance; or, Augmented Reality AND Maintenance); (ii) only open access articles were searched; (iii) time period from 2014 to 2019 was considered mature since the term "Industry 4.0" appeared by 2011. The research platforms used were: ScienceDirect and Archive Ouverte HAL. At the end, 59 articles were considered.

Third round. Finally, in the third round, I4.0 technologies applied in industrial maintenance were filtered and allocated into categories, regarding more tangible examples of them being applied in manufacture. The whole literature database ended with 87 articles and reports. From it, nine Maintenance-4.0 technology groups were identified: Big Data, Analytics, Artificial Intelligence and Cloud Computing, formalized as cyber-physical subgroup; Advanced Machines, Advanced Materials, Flexible Connection Devices and Digital-to-Real Representation (i.e. encapsulating Digital Twin applied in maintenance activities), formalized as application subgroup; and Sensors (i.e. encapsulating IoT and Smart Sensors, formalized as the bridge to digitalize physical operations).

2.3 Models and Requirements

To allocate maintenance into the conformities of I4.0 in an organized way, two different architectures were approached. The first, Framework for Enterprise Interoperability (FEI) from [19], was considerate by the premise that interoperability might be a relevant metrics to understand what can or cannot be implemented to a system. This possibility is considered because FEI relates conceptual, technological and organizational barriers linked between the enterprise layers, that could be generated by two systems trying to communicate. Coupled with that, the prerogative that interoperability barriers could difficult the insertion of a technology seems feasible, once legacy system and others adjacent systems/processes may share communication-dependence.

The second is a reference architecture model for Industry 4.0 (RAMI4.0) [18], converging multi-stakeholder views on how I4.0 can be accomplished based on existing communication standards and functional descriptions [20]. Analogously to the FEI, which has a broad organizational view but it is not linked to Industry 4.0, the RAMI4.0 presents a similar enterprise's layers perspective. Considering that this research investigates interoperability barriers which might appeared by implement I4.0

technologies in maintenance legacy systems, those frameworks were merged (see Fig. 2).

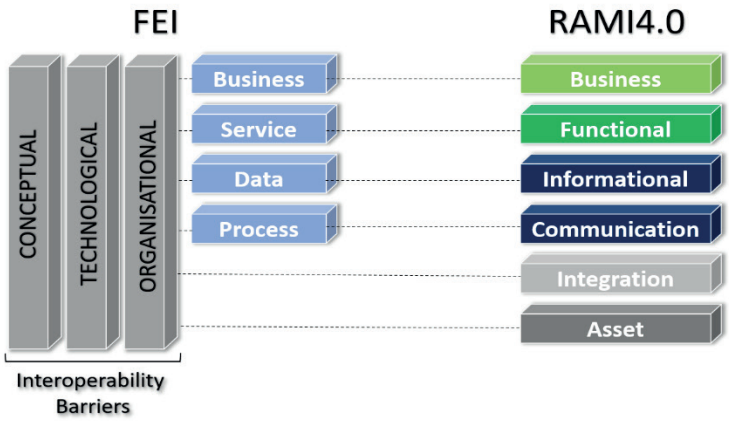

Fig. 2. (FEI barriers) x (RAMI4.0 layers) composed frameworks.

This composed framework was used to promote interoperability elements to an I4.0 referential architecture. The following section explains how industrial maintenance was focused in such vision.

As-is functions. The work [21] describes a study of industrial maintenance through the lens of RAMI4.0 architecture, indicating attributes and functional requirements, which gives this present work directions in how to analyses maintenance systems in an a priori state. Further, the presented case study details this analysis.

To-be model. In order to achieve I4.0 requirements for the maintenance sector, the Total Productive Maintenance (TPM) six big losses [22], were also considerate (see Fig.3).

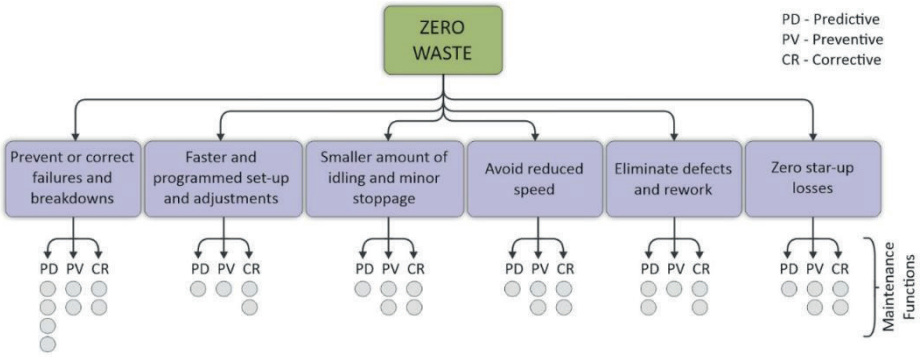

Fig. 3. Referential Maintenance-4.0 reference model based on TPM.

For those losses this model formalizes "courses of action", meaning that, for each loss there is a course of action based on I4.0 vision. Moreover, those courses of action are categorized in three main maintenance approaches: predictive, preventive and corrective [23]. Therefore, the spheres tagged as “maintenance functions” represent Maintenance-4.0 enablers for predictive, preventive and corrective approaches. Our premise is that, the full potential of a maintenance system can be achieved with the technology groups proposed in (2.2).

In resume, aiming to guide maintenance processes to “zero waste” using disruptive technologies, this proposed model serves as a To-be guide, for an As-is analysis [21], due to interoperability barriers. Alternatively, what is needed to implement (i.e. disruptive technologies) according to what is possible to be implemented (i.e. interoperability barriers).

2.4 MCDM

Multicriteria decision making/analysis (MCDM/A) methods, emerged in the search for solutions to complex problems that are difficult to measure. In this work they were used as tools for more assertive decisions in systems optimization, also following a couple of referential researches that applies decision making assessment in the dimensions of interoperability, maintenance and Industry 4.0 are [21, 24–28]**.**

There are four important elements that involve the MCDM methods: Set of “alternatives”, from which the decision is chosen; set of “criteria”, or factors related to making a good decision; the “preferences” of the decision maker, being clear, the problem becomes more understandable; and the “result” of each choice, measured in terms of criteria according to the decision maker's preferences.

Two different MCDM are used for the three steps framework, detailed in the next section. For the Step 01 and 02, the Analytic Hierarchy Process (AHP) [29] is used in order to derive priorities based on sets of peer comparisons, thus it is structured on the intrinsic ability of being to ponder their perceptions or ideas hierarchically [30]. In Step 03, the Preference Ranking Organization Method for Enrichment of Evaluations

(PROMETHEE II) is used, an interactive method designed to deal with quantitative, qualitative criteria and discrete alternatives. This method can classify alternatives that are difficult to compare due to a commitment to standards of evaluation as non-comparable alternatives [31]. According to [32] this method have been applied in varied fields such as industrial locations, labor planning, investments, medicine, chemistry, tourism and ethics.

3 Framework

The framework proposed in this article it is structured in three steps. In Step 01 the AHP method is used to assess the organization's maturity, relating the I4.0 requisites in a maintenance bias. In the Step 02 is also build for the application of AHP method, which will provide the allocation of weights for functions of a Maintenance-4.0 architecture, in order to obtain a selection of the most needed ones. Finally, at Step 03, the PROMETHEE II method will be applied to prioritize the technologies that will best adapt to the functions selected in the previous step (see Fig.4).

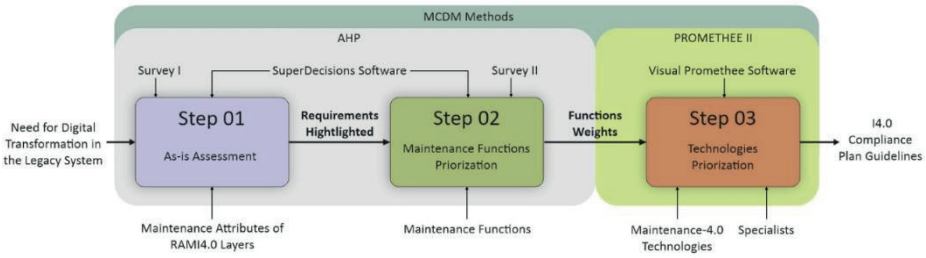

Fig. 4. Framework overview.

It is expected that after applying the framework, a legacy maintenance system will have its main requirements highlighted, indicating what needs to be improved according to I4.0 technologies. The decision methods analysis considers not only what needs to be implemented to improve the system, but also what is feasible through interoperability barriers.

3.1 Maturity Assessment (Step 01)

Once the organization's need to optimize its systems to I4.0 standards is confirmed, in Step 01 an assessment of its maturity in relation to the desired requirements is carried out. For this, engineers and maintainers must be made available, since they will be in the role of decision makers, answering the proposed survey model. Here the AHP method is executed in the "SuperDecisions" software. Its model reflects a maturity assessment that, through the construction of classification structures from the six layers of RAMI4.0, describes the decomposition of a machine in its structured properties, enabling its virtual mapping (see Fig. 5).

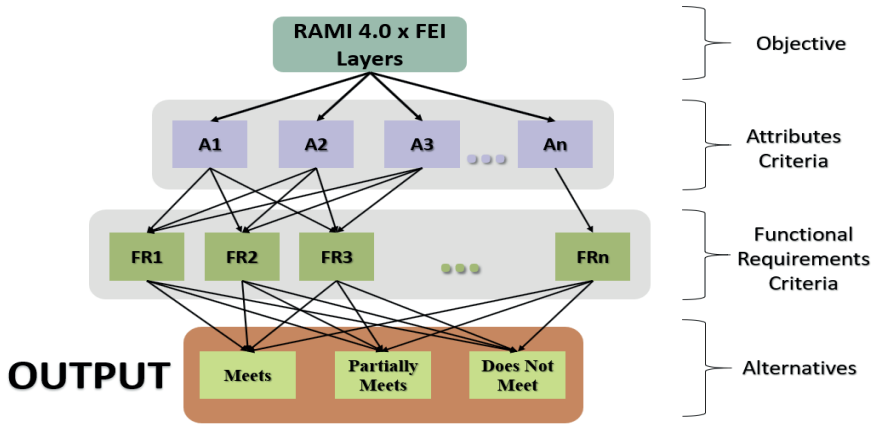

Fig. 5. Step 01 – Maturity Assessment (AHP method model 1).

The name of the analyzed layer will be located at the top level of the decision model, representing the model objective. The intermediate level will consist of attributes and functional requirements belonging to the domain of industrial maintenance, distributed among the six layers to be analyzed [21]. The relation, attributes-requirements, qualifies the analyzed system. At the end, the lower level presents the alternatives: meets, partially meets, and does not meet; related to each functional requirement of the intermediate level. After performing the peer review survey with the decision makers, with no inconsistency value identified by the software, it will perform the AHP synthesis in order to rank the three alternatives, thus providing the result of the maturity assessment for each layer of RAMI4.0. When all six layers are evaluated it will be possible to obtain the degree of maturity, related to the requirements of Industry 4.0.

3.2 Maintenance-4.0 Functions Prioritization (Step 02)

Having delimited the areas with the greatest lack of industrial maturity in Step 01, the objective of Step 02 is to prioritize the maintenance functions that will be used in the optimization process to implement I4.0 capabilities to the legacy systems analyzed. The AHP will be used again in order to assign weights to the functions accordingly to the preferences from the decision makers, not synthesizing the alternatives, as done previously (i.e., this step uses the method to gather the functions weights solely, and not to support a final decision).

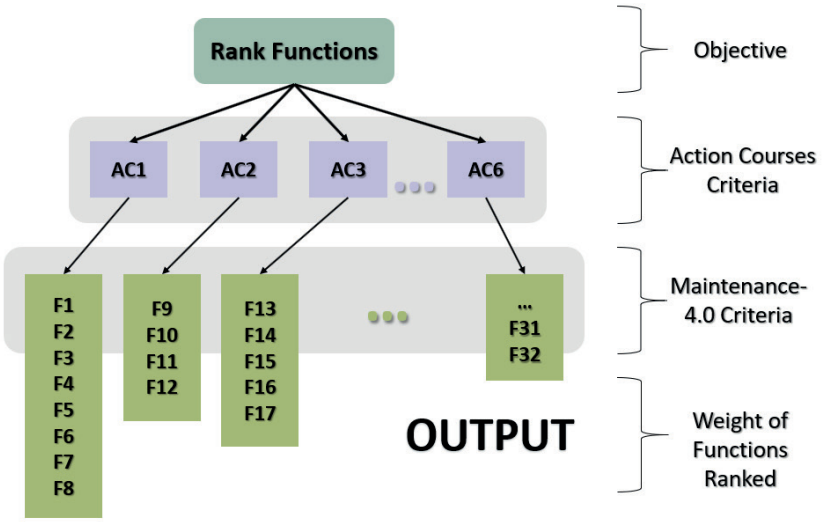

Fig. 6. Step 02 – Maintenance-4.0 Function's Rank (AHP method model 2).

At this stage, the survey reflects the Maintenance-4.0 model (see 2.3, To-be model), which presents a series of maintenance systems function's and their application in the light of I4.0. Based on the TPM's six main losses, the engineers and maintainers must consider their decisions regarding predictive, preventive and reactive approaches, that will guide maintenance processes to zero waste. At the end of the analysis, each function of the proposed Maintenance-4.0 model is ranked by weights in the AHP method in the "SuperDecisions" software, according to the decision makers preferences.

3.3 Maintenance-4.0 Technologies Prioritization (Step 03)

Based on the maintenance functions weighted in the previous stage, Step 03 objective is the prioritization of I4.0 technologies which best suit those functions. Here, the framework does not require a survey for engineers and maintainers, leaving the role of decision maker to a specialist. In the case study presented in section 4, one of the authors with access to the organization fill that specialist role. This suggests that is necessary an expert view of possible solutions to be used. The literature review on I4.0 technologies under the maintenance domain was used at this stage.

A decision model using the PROMETHEE II method in "Visual Promethee" software, was build. The weights of each Maintenance-4.0 function, from the previous step, will be inserted and related to the nine technology groups from the literature review. At the end of this analysis the software will provide several types of reports based on the hierarchy carried out by the method, and the specialist is responsible to decide the technologies necessary to cover the maintenance functions.

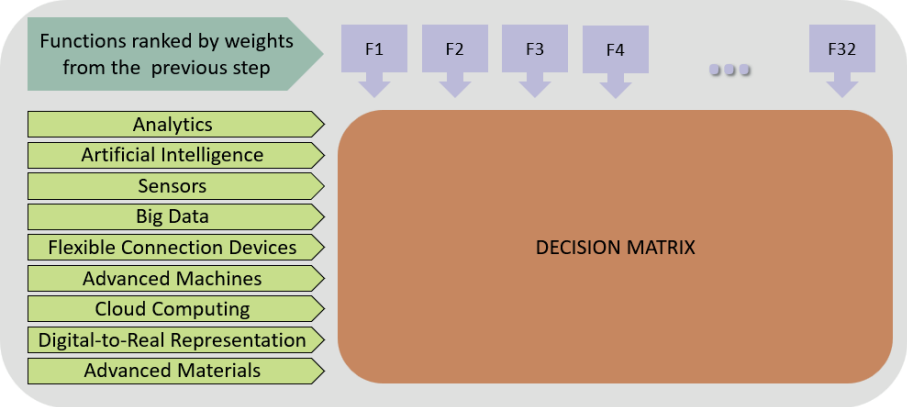

Fig. 7. Step 03 – Maintenance-4.0 Technologies Prioritization (Promethee method model).

After completing all the stages of the framework, there will be enough information for the specialist to develop assertive guidelines for an I4.0 compliance plan. Such plan suggests that: The Maintenance-4.0 technologies selected in the Step 03 enable the functions prioritized in the Step 02, which will act on the diagnosed areas arising from the Step 01 maturity assessment.

4 Results

To test the framework, a case study was applied to a multinational vehicle manufacturer. With a presence in more than 120 countries, the manufacturing complex in the southern region of Brazil employs approximately 8 thousand employees and has a production capacity of 320 thousand vehicles per year. We sought an area that offered a wider range of equipment, which is why the recently expanded engine factory has become the best option, mixing a wide range of modern and antique machinery. In Step 01, the industrial maturity assessment made in the "SuperDecisions" software, resulted in the analysis from Fig. 8, accordingly to the maintainers and maintenance managers' preferences.

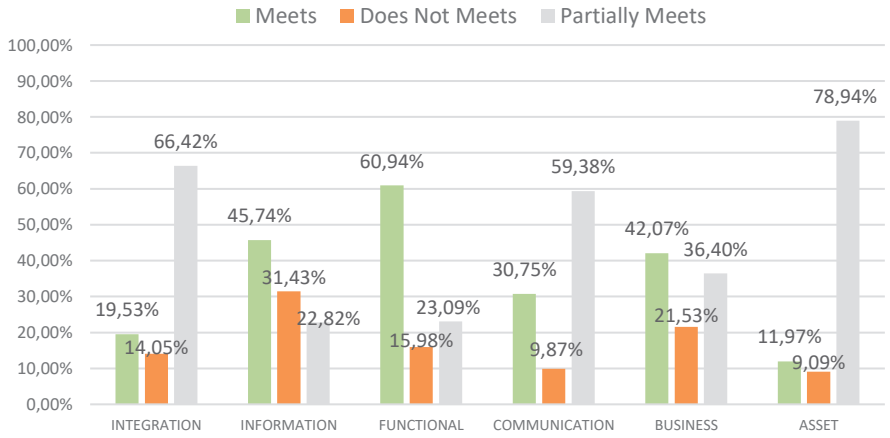

Fig. 8. RAMI 4.0 Layers individual Interoperability Assessment from AHP model 1.

Based on RAMI4.0/FEI, and again, following the preferences of managers and maintainers in the role of decision makers, the Information, Functional and Business layers presented the degree of adequacy "meets" while the Integration, Communication and Asset layers are classified as "partially meets". Also, with a deeper analysis, even though Business and Information layers meets the level of maturity, in both cases the alternatives "does not meets" and "partially meets" together exceeds 50%. This means that the AHP method is pointing out the preference (i.e. acknowledgement) of decision makers, that the factory is at a level that "meets" the requirements, but with more uncertainty than the "Functional" layer, for example. Such fact highlights the importance of choosing decision makers whom knows their processes and systems.

In the second stage, the maintenance functions of the Maintenance-4.0 model were ranked by relevance level, also following the preference of the same decision makers from the previous stage. Because this works focused in the application of the decision-making methods for adequacy of systems, this rank will not be displayed.

For Step 03, one of the authors played the role of decision maker as specialist. Using the "Visual Promethee" software, the weights of the functions obtained in Step 02 were inserted, and chosen by their level of need (i.e., syntactic graduation from 1 to 9), measured with the nine groups of Maintenance-4.0 technologies, as alternatives. Table 1 presents the ranking of the nine most relevant maintenance technology groups to meet the functions required to achieve a Maintenance-4.0 system, where phi, represents the preference index used by the method.

Table 1. Table captions should be placed above the tables.

Rank	Technology	Method Relevance
1st	Analytics	Phi 0,4245
2nd	Artificial intelligence	Phi 0,3455

3rd	Sensors	Phi 0,2342
4th	Big Data	Phi 0,1930
5th	Flexible Connection Devices	Phi 0,1713
6th	Advanced Machines	Phi 0,1566
7th	Cloud Computing	Phi -0,1923
8th	Digital-to-Real Representation	Phi -0,4994
9th	Advanced Materials	Phi -0,8334

It is noticed the predominance of technologies that operate at the Cyber-Physical level: Analytics, A.I. and Big Data, together with Sensors; being responsible to collect, interpret and store a large amount of data, enabling actions that are lacking in the factory, established in Step 02.

5 Conclusions and Future Works

The research developed here sought to answer the following research question: "How to define a technology prioritization plan, in the field of industrial maintenance, in order to adapt legacy systems for Industry 4.0 requirements?". For this, a framework was built, based on the RAMI4.0 and FEI architectures, assessing the maturity of legacy systems in the field of industrial maintenance under the requirements of I4.0 and considering interoperability barriers, with the hypothesis of providing assertive guidelines for adequacy plans for manufacturing industries. This need is part of the demand for adaptation to I4.0, where the reconditioning of legacy systems becomes the objective of organizations that seek to assign new functionalities to their equipment through digital transformation/modernization processes. Multicriteria decision making methods were the elements that encapsulated this work, giving a tooling bias to the framework.

Among the main difficulties encountered are the long questionnaires that need to be filled out in the steps. The professional involved spends a lot of time to fill them out, away from his activities. Although the framework has been positively validated, its complexity hinders its use. Many judgments are necessary and it is essential that all the components of the process are clarified in order to avoid mistaken considerations. With this in mind, parallel studies seek to alleviate the complexity of such digital transformation projects and open the scope for guidelines in addition to maintenance. A more mature initiative to design this framework will also be tested, using a different MCDM in the Step 02, solving only the most decisive Maintenance-4.0 functions, with the prerogative that "not everything that is necessary to implement, can actually be implemented – so the focus will be on the decisive aspects". This initiative could reduce the framework complexity focusing on decisive functions only. Further, this could be applied more than once, encountering new decisive functions each time the previous ones were resolved, corroborating with a gradual digital transformation.

Therefore, analogous with the empower of people with decision support tools, we emphasize as a final consideration that, digitalization of information, processes,

functions that make up the operations of a business and transforming the business's strategies are necessary, but not enough. Most importantly, digitalization is essentially about technology, but digital transformation is not. The digital transformation is about people. It is how to improve the quality people's life at work and how to improve the performance of organizations.

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The emergence of new business and operating models under the Industrial Digital Paradigm

Industrial Internet of Things (IIoT), Platforms, and Artificial Intelligence/Machine Learning (AI/ML)

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Abstract. This paper pretends to approach and analyse opportunities and risks that arises under the Industrial digital paradigm. Known by different names like Industry 4.0, Smart Manufacturing, or Production 4.0, among other terms digitalization in industry is advancing at a tremendous speed, and is pushing stablished firms to change and adopt new tools. Besides it opens opportunities to technological startups to deliver new products and services to the industrial market.

As an example of opportunities in operating models, it is clear that digitalization under the model Industry 4.0 and the advantages of Industrial Internet of the Things (IIoT), allows faster response to customer demands, increase flexibility allowing the adaptability to manufacturing processes, and provides a tremendous amount of tools for quality improvement in the processes, among other advantages.

This article addresses the data driven organization as digitalization evolves and the progress of Artificial Intelligence (AI) and Machine Learning (ML) solutions for industry.

Keywords: Industry 4.0, Industrial AI/ML, Data driven management.

1 Introduction

This work approaches one of the edges that shows the Industry 4.0 paradigm, and aims to explore opportunities and challenges that arise from its adoption, transforming traditional value chains to facilitate the creation of value and reach new levels of competitiveness.

The fourth industrial revolution, commonly termed as industry 4.0, is not just about industry. It is about overall transformation using digital integration and intelligent engineering. It is quoted as the next level of manufacturing where machines will redefine themselves in how they communicate and perform individual functions (Muhuri et al. 2019).

Another point of view about Industry 4.0 is given by Ibarra et al. (2017), according this work the new model has been brought into the manufacturing world by the increasing fusion of Industrial Production and Information and Communication Technologies (ICT). This phenomenon is making possible to connect information, objects and people due to the convergence of the physical and the virtual (cyberspace) worlds in the form of Cyber-Physical Systems (CPS). Therefore, it is enabling the transformation of factories into smart environments.

Sarmiento et al. (2020) stablish that a key principle of the Industry 4.0 paradigm is that processes and machinery must be networked as a collaborating community for the collection, exchange and analysis of data in order to predict future behaviours and pursue optimal solutions to possible problems. In the paper the author considers that nowadays, this principle is beginning to be achievable thanks to the development of a number of promising technologies. One of these technologies is the so-called Cyber–Physical Systems, which refers to systems with integrated computational and physical capabilities that can be interfaced in different ways. These systems are enhanced with features from the Internet of Things (IoT) technology, providing them with the ability to continuously obtain information from sensors or processes across the factory, and securely forward it to (generally cloud-based) data centres. This massive data production implies the development of new tools based on Big Data techniques, for storing, managing, and processing it. This set of technologies is completed with the Internet of Services (IoS) one, which takes the processed information from Big Data tools and deploys it at the right place and in the right form.

IoT is referred more specifically as Industrial Internet of Things (IIoT) when referred to its adoption in Industry. Porter and Heppelman (2015) uses the concept of IIoT and describes the way it makes possible to connect devices and obtain data from reading the devices. In the same work is explained that linking combinations of readings to the occurrence of problems can be useful, and even when the root cause of a problem is hard to deduce, those patterns can be acted on. Data from sensors that measure heat and vibration, for example, can predict an impending bearing failure days or weeks in advance. Capturing such insights is the domain of big data analytics, which blend mathematics, computer science, and business analysis techniques.

This paper pretends to go further from previous work regarding opportunities and risks that arises from digitalization, and specifically at the Industry 4.0 model and the emergence of new business models, Walas Mateo (2020). This paper pretends to go

deeper into opportunities around solutions on IIoT, platforms, and Artificial Intelligence/Machine Learning (AI/ML).

2 Conceptual Framework

To start the discussion of the subject it is aimed to approach, the definition de business operating model and business model by Iansity and Lakani (2020) it is put on consideration. The authors define that the value of a firm is shaped by these two concepts. The firm's business model, defined as the way the firm promises to create and capture value. The firm's operating model, defined as the way the firm delivers the value to its customers.

Searching for the drivers of competitiveness in digital business models under Industry 4.0 model, Grover et al. (2018) considers big data as a new yet powerful source for potentially immense economic and social value and for gaining a competitive advantage on par with an organization's capital assets and human talent. In this article it is affirmed that according to a 2016 report from PromptCloud, big data has grown from a $6.8 billion industry to a whopping $32 billion industry in just three years. IDC forecasts the market of big data technology and services to grow at a 23.1 percent compound annual rate, reaching $48.6 billion in 2019.1 Therefore with the volumes of organizational data moving past terabytes to tens or even hundreds of petabytes, businesses and information technology (IT) leaders are embracing unique opportunities to capitalize on big data to gain the competitive advantage. It is also considered in this article that companies are reported to spend more than 10 percent of their IT budget on data alone and are undergoing a revolution by leveraging big data and analytics (BDA) as a strategic asset to guide their decision-making and improve business processes and outcomes.

An interesting article about the evolution of Artificial intelligence (AI) is brought by Thomas Davenport (2018). In this work he states that analytics 4.0 is the next step in analytical sophistication for organizations, and it is the era of artificial intelligence or cognitive technologies. It became widely adopted – with adoption rates, depending upon geography, of 20 to 30% across large enterprises in 2016 and 2017. It features not only the use of AI methods, but also greater use of autonomy in the execution of the methods, particularly automated machine learning (ML).

A recent article by Davenport (2020), which is based on a research by Deloitte on the use of AI tools in Industry highlights how barriers to the adoption of artificial intelligence tools have decreased. Based on a survey of more than 2727 global executives from nine countries, and their organizations have all adopted AI. The key facts that emerge from the article is that the respondents feel that AI is getting easier, and will continue to do so.

Then there are two interesting insights from this article. The first one, is the preference for buying ready-made AI technology over building it. Indeed, at some point it will be difficult not to buy. Another item points that 74% of these executives agreed that "AI will be integrated into all enterprise applications within three years." In terms

of today's practice, 50% say they will either "buy all" of their AI capabilities. The second, is about the risks the adopter see about AI. Some of the specific risks that most concerned respondents were cybersecurity issues, AI failures that might affect business operations, misuse of personal data, and regulatory changes involving AI/ML.

Iansiti & Lakani (2020) conceptualize the Artificial Intelligence (AI) Factory as the core of the modern firm, where it is industrialized data gathering, analytics, and decision making. The AI factory is the scalable decision engine that powers the digital operating model, where value is created, of the twenty-first-century firm. Managerial decisions are increasingly embedded in software, which digitizes many processes that have traditionally been carried out by employees. Digital operating models can take various forms, AI factories are at the core of the model, guiding the most critical processes and operating decisions, while humans are moved to the edge, off the critical path of value delivery. From the concepts of these authors two points should be considered in this paper. The first one is transforming the industrial environment to an AI Factory environment, and the second one is the new role of the industrial operator or the industrial engineer.

A concept that needs to be consider when talking about new business models under Industry 4.0 paradigm is uncertainty. To cope with this fact, sensing and rapid response when planning a new strategy is critical. A tool that could help to develop and find a product and business model that really works is an Agile methodology called Lean Start Up. The real challenge is to develop and validate the value proposition, and look for a profitable business model that allows to consolidate sales and scale the volume of business.

The Lean Start Up methodology created by Eric Ries (2010), collecting the adjective "lean" widely disseminated when describing production methods developed by Toyota and other Japanese manufacturers for dispense with everything that is left over, hinders and lengthens the Productive processes. The fundamental objective of Lean Startup is shortening the product development cycle and employing agile development methods, with validation tests by the market, to match the processes to the acceptance of the clients, adjusting and pivoting -when needed-Indicators are used incremental to measure the result of the actions on the interested customers and sales and the model is analysed and controlled appropriate growth based on acquisition costs, of customer retention and the value of customers throughout its life cycle. In sum, a set of techniques for match the product development processes with the customer discovery and development.

A last issue to consider is what Ibarra et al. (2017) mention about the effects of the phenomenon considered as the Fourth Industrial Revolution. In the paper by this author is stablished that it will be the most powerful driver of innovation over the next few decades triggering the next wave of innovation. Thus, the main features related to the Industry 4.0 such as real-time capability, interoperability and the horizontal and vertical integration of production systems through ICT systems, are regarded to be the response to current challenges that companies must face to stay competitive in terms of globalization and intensification of competitiveness, the volatility of market demands, shortened innovation and product life-cycles and the increasing complexity around products

and processes. The adoption of data models, especially when working with heavy industries where is not possible to change to last generation equipment and machines, and digitalization could help to improve the performance of assets with decades in use in steel or energy generation industries.

3 Objective of the work, hypothesis of the research

Having enough evidence about the use and benefits of data analytics in the productive environment under Industry 4.0 framework, this work it is aimed to study and analyse opportunities and difficulties that arise to create new business and operating models from the use of IIoT, Artificial Intelligence and Machine Learning in the industrial environment to improve industrial processes.

This paper aims to take in consideration the issues in the above paragraphs, in the framework of the adoption of IIoT and AI/ML solutions. A key topic to explore is how open innovation, Lean startup and platforms, among other methodologies can help with the challenge that means the disruption that is produced in the industrial scenario when adopting data models.

A paper of the Boston Consulting Group (2015), states that the model Industry 4.0 allows faster response to customer demands, increase flexibility allowing the adaptability to manufacturing processes, and provides a tremendous amount of tools for quality improvement in the processes, among other advantages.

Another observation that is object of this work is what is said by Muhuri et al. (2019) about studies that have shown that digitization of products and services has become a necessity for a sound industrial ecosystem. However, these requirements and advanced technologies have made the systems more complex and led to many other challenges such as cybersecurity, reliability, integrity, etc. These are the major bottlenecks which needs to be overcome for the successful design and deployment of Industry 4.0.

This work aims to approaches one of the edges that shows the Industry 4.0 paradigm, and to explore opportunities and challenges that arise from its adoption, transforming traditional value chains to facilitate the creation of value and reach new levels of competitiveness.

4 Some interesting findings

Iansiti & Lakhani (2014) establish in their work that adapting to ubiquitous digital connectivity is essential to competitiveness in most sectors of the economy. They reinforce the concept by saying that they have examined transformation across dozens of industries and companies—both traditional and born-digital, talked to hundreds of executives in an effort to understand how traditional modes of innovation and operational execution are changing. (Disclosure: they have consulted with or have interests in several of the companies mentioned in their article.) They have seen that digital transformation is no traditional disruption scenario: The paradigm is not displacement and replacement but connectivity and recombination.

The concept product as a service has broaden to anything-as-a-service (XaaS). An article from Deloitte, by Sharma et al (2019) suggest that the ever-changing technology landscape—currently shaped by technologies such as cloud computing, anything-as-a-service (XaaS), and the Internet of Things (including industrial IoT)—has solidified the need for businesses to adopt a customer-in mindset, shifting focus from selling a product to nourishing a customer relationship: understanding expectations and maximizing customer value from offerings.

Walas Mateo (2020) give a brief description of how the robotic industry is changing business models through connected products with the case of Universal Robots (UR). Today it is possible for UR industrial robots and other robots suppliers to implement as a service business models to facilitate any firm to afford having a robot. Beyond that UR introduced the concept of collaborative robot or cobot, making possible human and robots to work very close each other in the industrial environment.

In this work Walas Mateo (2020) points that there are three different kind of disruptive business models, some of them derivate from digital transformation, economy of platforms, decentralized models or superfluid economy. The new business models and the companies that represent them lean on a series of repeating premises: personalization, pay per use, collaborative model, agile and flexible organizational models, and the data.

The paper of the BCG (2015) approach the cooperation in Industry 4.0 where companies, departments, functions, and capabilities will become much more cohesive, as cross-company, universal data integration networks evolve and enable truly automated value chains. In this line, it is presented an example of how Dassault Systemes and BoostAeroSpace launched the platform AirDesign, for the European aerospace and defense industry as a common workspace for design and manufacturing collaboration. This platform is available as a service on a private cloud. In this way it can be managed the complex task of exchanging product and production data among multiple partners.

Iansiti & Lakhani (2020), refers to platforms and their integration that allows an effect of extraordinary scope when talking about digital operating systems, allowing disruptive business and work models. The authors especially mentions Alibaba and Amazon cases. A platform is an environment where an application runs, and based on network connectivity, this definition has been extended to a space where different users can interact with each other or with physical objects. As a result, suppliers, customers, and other partners become part of a networked ecosystem around the CPS.

The integration and scope of the platforms are generated by being connected through APIs. An API, an acronym for Application Programming Interface, is the mechanism that allows devices and platforms to be integrated. It is something that facilitates, for example, that applications using georeferencing to access information from Google Maps.

This phenomenon of liquid marketplace, as it is called by Iansiti & Lakhani (2020) from the possibility that generates Internet and ubiquity, makes possible to reconfigure global value chains, and integrate different platforms to make easier operations management.

In line with this Walas Mateo (2020) presents the case of the European network of Kiala that count on 7,200 Points and 1,050 Click & Collect Points distributed in 5 European countries. In this way the company offers a delivery service without a single drop-off or pick- point in a building of its own. This is an example of a new level of liquid business that is becoming increasingly common.

An interesting view regarding innovation, platforms, and digital disruption is brought by Cozmiuc, & Petrisor (2018) they say that business models have become key to digital disruption, and the latest business models shift from pipeline material flow to knowledge creation in platforms. They remark the importance of open innovation as part of platform business models, and that business models are now financed directly, which has created the lean startup movement. Startups enter markets with no barriers and force incumbents to race them with the ability to compete based on business models and match start-up agility and creativity. In this work they describe the case of the world's top innovators, Siemens, and the way the company uses the latest tools for innovation: open innovation for technology invention, business models to turn invention into innovation, and finances business models. Siemens has created an inner structure that intends to bring the advantages of the lean start-up movement indoors.

In the framework of what is described above, arise the Siemens Next47 initiative. According to Hilse & Susemihl (2018) in their work on successful cooperation between companies and startups, develop the case extensively. It is an accelerator of technological startups with products and services for IIoT, AI/ML, and other disruptive digitization solutions.

In Gradient Ventures, Google's AI-focused venture fund investing in and connecting early-stage startups with resources in artificial intelligence. Searching in its portfolio of startups founded, Canvass Analytics, www.canvass.io, is one of them. This startup that aroused interest for this research had developed a business model based on an AI-powered predictive analytics platform for Industrial processes. Its customers include leading manufacturing and energy companies globally.

At its web site the startup says that its platform automates the entire data science process, eliminating consulting data science projects. They affirm that the platform approach has accelerated the time to insights 12 times faster than other solutions and approaches. The solution is developed specifically for the industrial sector.

A paragraph in the findings deserves the importance of the Customer when adopting a new business model. Cornella & Planellas (2020) conclude in their work that customers will also be part of the company, especially those who prove to be the best 'sensors' for real demand.

At the end, it should be considered the success in adoption of the new models. An interesting aproach is given by Sailer (2019) in a paper where it is stated that it has been identified three key imperatives in successful digital transformations. These imperatives have shaped their Integrated Change Management methodology:

- Instituting an integrated approach across facts – i.e., tangible elements such as technology, processes and social interactions – i.e., intangible elements such as culture and teams throughout the transformation journey and across the entire company.

- Living agile by proactively updating change measures to meet both current needs and overall objectives effectively
- Adapting "classic" Change Management levers such as communication, leadership, team setup, training, etc. for digitalization needs

5 Conclusions and future work

Different firms in a broad spectrum of sectors are shifting value from manufacturers and distributors to companies that operate end-to-end platforms and provide outcomes as-a-service. Many firms face growing threat of market obsolescence, and then constant change seems to be the golden rule.

Regarding the role of the customer and operators in the shop floor, seems people have a central role in new operating and business models. It can be said that each new opportunity will require the participation of people and departments who are today isolated in their silos, and so creating multidisciplinary teams. Collaboration with other companies will be the norm once it is understood that the world is too complex to be solved in isolation.

A point to consider when thinking in new operating or business model in any firm, is the need for agility. A Lean startup approach to test the new model and go for a fast ROI seems a good option.

This paper left some questions to be studied in future work. The first one in this line of research, is the data driven organization as IoT evolution from leading edge innovation mainstream technology and its business potential. Also very important is to watch the progress of Artificial Intelligence (AI) solutions for industry, such as those presented by new technological startups. New firms appear everyday to provide tools for smart manufacturing environments, capturing and delivering value in Industrial environment. New companies like LLamasoft, which provides AI for supply chain management (SCM), and the mentioned before in this paper, Canvass Analytics are examples of this dynamic.

Another key topic to explore in future work, is how process operators or industrial engineers can cope with the challenge that means the disruption that is produced in the industrial scenario when adopting data analytics models. Therefore the question is the way the shop floor will capture the value that generates the AI/ML, should the process operator or industrial engineer at the process level go further in the master of analytics tools, or the solutions that managers should buy according to Davenport (2020) will be tuned to the language and needs of the people that work in the process.

Finally, another issue that awake curiosity regarding AI/ML as process optimization driver is the integration with IoT and its evolution from leading edge innovation mainstream technology, and potential to produce data to feed AI/ML models.

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Análise de Maturidade da Indústria 4.0: foco em Países Emergentes

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Abstract. A Indústria 4.0 é o novo estágio produtivo que está impulsionando a quarta revolução industrial, muitas empresas esperam um impacto significativo em suas operações, cadeia de suprimentos e modelos de negócios. As dificuldades de adaptação a esta nova abordagem colocam desafios para as empresas de Países Emergentes, tanto pela complexidade de suas características, que ainda não foram compreendidas totalmente, quanto pelas suas limitações derivadas de seus países onde atuam. Para implementar um roteiro de forma adequada, ferramentas como Modelos de Maturidade (MM) podem ser muito úteis, pois auxiliam na avaliação do estado inicial da organização e no planejamento de um roteiro de desenvolvimento. Nos últimos anos, diversos MMs foram desenvolvidos para a Indústria 4.0, alguns deles para contextos de aplicações específicos. No entanto, não há nenhum modelo desenvolvido especialmente para os Países em Desenvolvimento. Este artigo, apresenta um novo MM para esse contexto, o modelo é composto por sete dimensões e cinco níveis de maturidade para cada dimensão. A metodologia abrange uma etapa multicriterial, com a aplicação do método Processo de Análise Hierárquica (AHP) e 2-Tuple. Por se tratar de um estudo preliminar, a aplicação e validação do modelo é esperada em uma etapa futura no desenvolvimento do modelo.

Keywords: Indústria 4.0, Países Emergentes, Modelo de Maturidade.

1 Introdução

A Indústria 4.0 pode ser entendida como um novo estágio industrial e, atualmente, o qual se trata de um dos tópicos mais populares nos campos profissional e acadêmico [7] [21]. Este conceito tem o smart manufacturing como seu elemento central [16]. A indústria 4.0 depende da adoção de tecnologias digitais para coletar dados em tempo real e analisá-los, fornecendo informações úteis ao sistema de manufatura [20]. Isso é possível, graças ao advento da Internet das Coisas (IoT), big data, analytics e serviços em nuvem, criando o conceito cibernético da Indústria 4.0 [40] [22].

Espera-se que a Indústria 4.0 tenha um impacto significativo na cadeia de suprimentos, no modelo de negócios e processos. De acordo com [16], as mudanças fundamentais que serão possibilitadas pela quarta revolução industrial são as seguintes: flexibilidade, tomada de decisão otimizada, atendimento personalizado aos clientes, produtividade e eficiência de recursos, criação de valor através de novos serviços dentre outras.

No entanto, a adoção de tecnologias avançadas para os países emergentes pode ser mais desafiadora [14] [18]. Uma vez que os países emergentes têm sua economia mais direcionada à extração e comercialização de commodities, as empresas destes países estão frequentemente atrás em termos tecnológicos quando comparadas com seus similares nos países desenvolvidos [6]. Fatores como cultura, nível de escolaridade, instabilidade econômica e política e infraestrutura de TIC, também podem impactar na percepção de valor e, consequentemente, no nível de investimentos em tecnologias avançadas [10].

Quando se fala em países emergentes, não se pode deixar de citar os países que compõem o BRICS e as rupturas tecnológicas que impactaram de forma positiva no desenvolvimento de suas economias. Para o Brasil, a Rússia, a Índia e a África do Sul, as rupturas ocorreram imediatamente após o fim da Guerra Fria, durante o período 1991-94. Após o restabelecimento da democracia em 1986, o Brasil implementou o Plano Real de ajuste estrutural em 1994; a Rússia, após o colapso da União Soviética, experimentou um "tratamento de choque" através da rápida adoção do livre mercado em 1992; a Índia começou a liberalizar a "licença Raj" de 1991 em diante, e, em 1994, a África do Sul pós-apartheid iniciou sua longa caminhada na direção da liberdade política e econômica. A China seguiu por um caminho diferente e, seguindo as reformas fundiárias e da agricultura de 1949 aos anos 1960, começou sua segunda Longa Marcha em 1978, desta vez pela via do capitalismo [37]. Essas rupturas, tiveram impacto no momento atual, no entanto, frente a Quarta Revolução Industrial ainda não se desconhece os impactos destas recentes rupturas.

Muitas empresas enfrentam o desafio de avaliar a diversidade de desenvolvimentos e conceitos sob o termo Indústria 4.0 e desenvolver suas próprias estratégias corporativas [2]. As empresas instaladas em países emergentes tentam remodelar suas operações de acordo com tecnologias emergentes, com o objetivo de permanecerem competitivas e garantir a continuidade no mercado. Como a Indústria 4.0 está nos estágios iniciais de seu desenvolvimento, a definição da estrutura e a metodologia das diretrizes de implantação se torna essencial [11]. Sendo assim, há uma demanda em ajudar as organizações que estão fazendo essa transição para o novo ambiente industrial e também orientá-las para a melhor utilização de seus recursos.

Abordagens estruturadas, como modelos de maturidade (MM) ou estruturas de apoio, tem por objetivo ajudar as organizações, fornecendo orientações abrangentes e permitindo avaliar um roteiro adequado de implementação sustentável das novas tecnologias do novo paradigma. A noção de maturidade é usada para definir, avaliar e formar uma diretriz e uma base para mensurar a evolução nos negócios, ou seja, a maturidade de um processo ou de uma tecnologia [26]. A ideia principal para a utilização do MM é descrever o nível de perfeição de uma organização, como um novo modelo de negócio empregado ou um novo processo desenvolvido. Outra suposição para o uso de MM é que à medida que o grau de maturidade se torna maior, um progresso melhor é alcançado em aspectos diferentes que contribuem para a evolução da organização. Sendo assim, o modelo de maturidade é considerado como uma linha de base deste estudo.

Diante deste contexto, este artigo analisa os modelos de maturidade disponíveis atualmente para Indústria 4.0. Em seguida, ele discute os modelos de maturidade em relação à sua "adequação" as economias emergentes. No processo, se discute as lacunas da pesquisa e, finalmente, propõe-se uma possível via para resolvê-las, criando ou adaptando um modelo de maturidade dedicado para as economias emergentes.

2 Referencial teórico

2.1 Construção do Portfólio Bibliográfico

Para composição da base teórica deste trabalho, foi realizado o processo de revisão sistemática da literatura. As bases *Web of Science*, *Scopus* e *Science Direct* foram selecionadas, as quais, seguindo critérios de classificação, possuem artigos de maior relevância sobre o tema.

Para realização desta pesquisa, foram definidos eixos de pesquisa onde os mesmos foram formados pelos tópicos Indústria 4.0, Modelos de Maturidade e Países Emergentes. Realizou-se combinações de palavras através da utilização de palavras-chaves propostas para cada eixo. Foram utilizadas as palavras-chave “smart manufacturing”, “Industry 4.0”, “*fourth industrial revolution*”, “*assessment*”, “*maturity model*” e “*emerging markets*” de modo a abranger todo o conteúdo relacionado a temática.

Após as combinações das palavras-chave e a definição dos critérios a serem utilizados para as buscas, todos os artigos resultantes foram agrupados, obtendo um resultado de 10 artigos, conforme pode ser conferido na Tabela 1. Esse portfólio bibliográfico é constituído pelos MM resultantes de nossa pesquisa e serão utilizados como base para o desenvolvimento do nosso trabalho.

Tabela 1. Portfólio de Pesquisa

Título	Autores
Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice	Wagire, Anituddha; Joshi, Rohit; Rathore, Ajay; Jain, Rajesh
An Industry 4.0 maturity model proposal	Santos, Reginaldo; Martinho, José

A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era	M. Colli; U. Bergerb; M. Bockholta; O. Madsena; C. Møllera; B. Vejrum Wæhrens
Defining and assessing industry 4.0 maturity levels – case of the defense sector	Bibby, Lee; Dehe, Benjamin
Three Stage Maturity Model in SME's	Ganzarain, Jaione; Errasti, Nekane
Development of an Industry 4.0 maturity model for the delivery process in supply chains	Asdecker , Björn; Felch, Vanessa
A fuzzy rule-based industry 4.0 maturity model for operations and supply chain	Caiado, Rodrigo; Scavarda, Luiz; Gavião, Luiz; Ivson, Paulo; Nascimento, Daniel; Garza-Reyes, Jose
A Maturity Level-Based Assessment Tool to Enhance the Implementation of Industry 4.0 in Small and Medium-Sized Enterprises	Rauch, Erwin; Unterhofer, Marco; Rojas, Rafael; Gualtieri, Luca; Woschank, Manuel; Matt, Dominik
An Industry 4.0 maturity model for machine tool companies	Lizarralde, Rafael; Ganzarain, Jaione; López, Cristina; Serrano, Ibon
Digital readiness assessment of Italian SMEs: a case-study research	Pirola, Fabiana; Cimini, Chiara; Pinto, Roberto

2.2 Indústria 4.0 nos Países Emergentes

A Indústria 4.0 tem como alvo a implementação de estruturas e processos interconectados, inteligentes e autocontrolados de processos e sistemas [1]. Portanto, os processos de negócios baseados nas tecnologias subjacentes à Indústria 4.0 fornecem processos inovadores de valor agregado, proporcionando operações mais flexíveis, confiáveis e eficientes. Em geral, os últimos desenvolvimentos em tecnologia por si só oferecem novas oportunidades e criam novos modelos de negócios; enquanto a Indústria 4.0 é vista como um desenvolvimento tecnológico disruptivo que traz uma inovação no novo modelo de negócio no setor manufatureiro [16]. Como ainda está em fase inicial de desenvolvimento, é essencial definir a estrutura e a metodologia das diretrizes de implementação da Indústria 4.0 nas organizações para que esse processo seja bem sucedido.

A Indústria 4.0 tem origem em países desenvolvidos, que possuem os conceitos da terceira revolução industrial já desenvolvidos como o uso das TIC`s (tecnologias de informação e comunicação) e automação, sendo conceitos inerentes à Indústria 4.0 [16]. Nesse sentido, países emergentes podem enfrentar uma lacuna importante para implementação da Indústria 4.0 em função da baixa maturidade dos estágios industriais de terceira revolução industrial [17]. No contexto da indústria brasileira, a adoção da TIC aumentou significativamente, ocasionando uma melhora na produtividade industrial [9]. Contudo, no estudo de [10] através de um levantamento em larga escala da indústria brasileira, os investimentos em software não incorreram em resultados positivos em se tratando de benefícios de mercado ou melhoria interna nos processos de fabricação. Os autores argumentam que as empresas estão automatizando suas rotinas operacionais e não objetivando a busca de ferramentas avançadas de TIC para ganho de vantagem competitiva real no desenvolvimento da inovação [10].

No mesmo estudo, com relação às tecnologias de fabricação, os autores argumentam que a estratégia de aquisição de máquinas e equipamentos não trouxe benefícios satisfatórios em inovação quando comparadas a outras atividades de inovação de indústrias no Brasil. Os autores sustentam a ideia de que a maioria das empresas não adquire tecnologias de ponta – como da Indústria 4.0 -, mas apenas aquelas necessárias para a atualização de equipamentos antigos [10], estudos anteriores em países emergentes corroboram esta afirmação [41]. Outro fator relevante que impacta diretamente na inovação em países emergentes, refere-se ao fato de que a população destes países possui renda mais baixa que de países em desenvolvimento, o que torna os produtos de baixo custo preferíveis no consumo e, por consequência, o fator competitividade sobressaindo sobre a inovação [27]. Esse comportamento de Mercado pode influenciar diretamente os investimentos em tecnologia. Normalmente, empresas de países emergentes estão mais propensas a investirem em tecnologias já estabelecidas para ganhos de produtividade ao invés de investirem em tecnologias avançadas para diferenciação de produtos. Dessa forma, pilares base da Indústria 4.0 – TIC e automação – encontram-se em um estágio aquém do esperado para o avanço ruma a quarta revolução industrial.

Desafios estruturais enfrentados pelas economias de países emergentes também podem impactar no processo de adoção das tecnologias da Indústria 4.0. Um desses desafios diz respeito à cadeia de suprimentos da indústria da manufatura, pois tende a ser menos integrada em comparação aos países desenvolvidos [24] [23]. A força de trabalho de baixo custo, em especial nas atividades de manufatura, pode desencorajar ou atrasar investimentos em automação e tecnologias avançadas, visto que são mais caras nesses países [32]. Poucos investimentos em P&D [29], instabilidades política e econômica [14] são mais alguns exemplos que configuram um cenário desfavorável para adoção de tecnologias da Indústria 4.0.

Está claro que os desafios para adoção de tecnologias da Indústria 4.0 em países emergentes são diferentes daqueles em países desenvolvidos. Por se tratar de um conceito relativamente novo, existe uma alta incerteza e falta de conhecimento sobre o verdadeiro impacto e contribuição dessas tecnologias no contexto de países emergentes em sentido geral. Isso torna ainda mais importante a definição da estrutura e das metodologias de implementação da Indústria 4.0 nas organizações. A fim de investigar o sucesso da maturidade de fabricação no contexto da Indústria 4.0, vários modelos de maturidade já foram desenvolvidos, conforme será discutido adiante.

2.3 Modelos de Maturidade da Indústria 4.0

Um modelo de maturidade pode ser definido como uma estrutura conceitual, constituído por partes que definem a maturidade, ou o estado de desenvolvimento, de uma determinada área de interesse, e em alguns casos identifica e descreve processos que uma organização precisa desenvolver para atingir um determinado cenário futuro desejado. Estes modelos tipicamente contemplam dimensões e níveis. O conteúdo de cada dimensão pode ser derivado de métodos qualitativos de pesquisa, incluindo estudos de caso, grupos focais, e outras metodologias de geração de ideias e tomada de decisão [28]. Os níveis são rótulos ordinais que significam estágios de maturidade, enquanto as dimensões representam capacidades específicas do domínio de interesse. Um nível de

maturidade consiste na consolidação de práticas gerais e específicas relacionadas a um conjunto de processos predefinidos que aumentam a performance geral de uma empresa, ou de um objetivo específico [36].

A transformação para a Indústria 4.0 envolve um aumento significativo das competências digitais na manufatura, e provoca mudanças ao longo de toda a organização. Considerando a alta complexidade desta transformação, é esperado que ela leve muitos anos, e deve ser planejada e implementada de modo a garantir impactos positivos na lucratividade, por exemplo através de ganhos de eficiência, e deve ocorrer em etapas incrementais. Pode não ser exatamente sincronizada em todos os processos de negócio, todas as plantas industriais, linhas de produção, ou mesmo em todas as células de produção em uma unidade. Fica a critério de cada empresa decidir qual estágio de desenvolvimento que representa um bom equilíbrio entre os custos e os benefícios da mudança, de acordo com as circunstâncias que envolvem o negócio, com a visão de um estado futuro desejado ao final do processo de transformação [35].

Antes de engajarem-se em projetos ou atividades de transformação, as empresas de manufatura precisam reconhecer o estado atual de aderência aos conceitos e tecnologias da Indústria 4.0, através de uma análise sistemática e estratégica, que envolva não somente o desempenho da empresa em si, mas de todas as partes envolvidas no negócio, tais como fornecedores, clientes e investidores.

Desta forma, serão apresentados e analisados os modelos que avaliam a maturidade na Indústria 4.0 encontrados através da revisão de literatura (Tabela 1). A partir da pesquisa bibliográfica, foram estudados alguns modelos de maturidade da Indústria 4.0, com objetivo de conhecer o que existe na literatura, e para fundamentar a aplicação do novo modelo, que contemple as melhores práticas dos modelos existentes (Tabela 2):

Tabela 2. Modelos de Maturidade da Indústria 4.0

Artigo	Dimensões	Níveis	Limitações
Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice	Pessoas e Cultura; Conscientização da Indústria 4.0; Estratégia Organizacional; Cadeia de Valor e Processos; Tecnologia de Manufatura Inteligente; Tecnologia Orientada a Produtos e Serviços; Tecnologia de Base da Indústria 4.0	Outsider; Iniciante Digital; Experiente; Especialista	- opinião dos especialistas com certo nível de subjetividade
An Industry 4.0 maturity model proposal	Estratégia; Estrutura e cultura organizacional; Força de trabalho; Fábricas inteligentes; Processos inteligentes; Produtos e serviços inteligentes	Baixo; Desenvolvimento; Iniciado; Parcial; Avançado; Referência	- pequeno número de profissionais que participaram da validação do modelo

A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era	Governança; Tecnologia; Conectividade; Criação de valor; Competências	Nenhum; Básico; Transparente; Informado; Autônomo; Integrado	- ferramenta apresentada precisa ser refinada e tornada mais robusta; - grande necessidade de recursos, limitando a aplicação em PMEs
Defining and assessing industry 4.0 maturity levels – case of the defense sector	Fábrica do futuro; Pessoas e cultura; Estratégia.	Mínimo; Desenvolvimento; Definido; Excelência	- design da estrutura pode favorecer uma organização mais focada em uma característica tecnológica.
Three Stage Maturity Model in SME's towards Industry 4.0	Visão; Capacidade; Ação	Inicial; Gerenciado; Definido; Transformado; Modelo de Negócios Detalhado.	Não apresenta
Development of an Industry 4.0 maturity model for the delivery process in supply chains	Processamento de pedidos; armazenamento; envio	Digitalização básica; digitalização entre departamentos; digitalização horizontal e vertical; digitalização completa; digitalização completa otimizada	- opiniões e julgamento de especialistas conferem certo grau de subjetividade; - população e processo de avaliação do modelo com viés regional;
A fuzzy rule-based industry 4.0 maturity model for operations and supply chain management	*Supply Chain Management*; Produção e Gerenciamento de Operações & *Supply Chain Management*; Produção e Gerenciamento de Operações	Não existente; Conceitual; Gerenciado; Avançado; Auto otimizado	- não avaliado em diferentes contextos
A Maturity Level-Based Assessment Tool to Enhance the Implementation of Industry 4.0 in Small and Medium-Sized Enterprises	Operações; Organização; Sócio Cultural; Tecnologia	Cinco níveis foram definidos onde cada um dos 42 itens possui sua descrição	- esforço de avaliação alto (tempo dispendido para realização)
An Industry 4.0 maturity model for machine tool companies	Funcionários; Estratégia e organização; Fábrica Inteligente; Orientação à Dados; Operações Inteligentes; Produtos Inteligentes	Não iniciado; Iniciante; Intermediário; Experiente; Especialista; Melhores desempenhos	Não apresenta

Digital readiness assessment of Italian SMEs: a case-study research	Estratégia; pessoas; processos; tecnologia e integração	DRL 1; DRL 2; DRL 3; DRL 4; DRL 5	Não apresenta

É possível observar que os artigos não levaram em conta todos os componentes contextualizados sobre a Indústria 4.0, como por exemplo, recursos voltados para segurança de informação. Verifica-se assim, que os modelos não trazem todas as informações necessárias para analisar a maturidade da Indústria 4.0, tendo em vista que o tema vem sendo construído, bem como seus conceitos, características e componentes, o que mostra a necessidade de melhoria e evolução dos modelos.

A partir dos modelos de maturidade descritos nota-se a ausência de uma abordagem voltada para as organizações de países emergentes, estas por sua vez, possuem um ambiente organizacional mais fraco e menos sofisticado e isto traz implicações para a estratégia e para a gestão destas empresas [12]. Diferentemente das organizações de países desenvolvidos, estas organizações sofrem forte influencia segundo aspectos de custos de operação, sistemas de distribuição, relacionamento com governos e infraestrutura de comunicação, aspectos estes que merecem atenção pois podem afetar o desenvolvimento da Industria 4.0 dentro destas organizações.

3 Metodologia

Modelos de maturidade geralmente definem seus níveis em termos de componentes e subcomponentes, e esses elementos são validados principalmente com o auxílio de pesquisas dentro das indústrias [19]. Dessa forma, os modelos de maturidade se tornam viáveis para apoiar as empresas de manufatura em países emergentes na realização com sucesso a avaliação e implementação dos recursos da Industria 4.0.

Ao adotar o modelo proposto, uma organização poderá avaliar, dentro das dimensões propostas, e se posicionar dentro dos níveis de maturidade para cada dimensão. Assim, a organização é capaz de identificar os pontos necessários para alcançar o nível seguinte de maturidade em uma determinada dimensão.

3.1 Identificando as dimensões com base na revisão de literatura

A indústria 4.0 trata da conectividade, integração dos sistemas de manufatura e vai além. O foco está nos ganhos das operações de fabricação. A exposição destes cenários irá impactar positivamente no desenvolvimento da Indústria 4.0 tendo em vista que as organizações têm de buscar o equilíbrio em diferentes fatores decorrentes do avanço dos sistemas de fabricação [38]. Essas informações foram levadas em consideração ao projetar as dimensões incluídas no modelo de maturidade (Tabela 3). Todas foram designadas com base na perspectiva de uma organização que opera em um país emergente com suas premissas específicas.

Tabela 3. Dimensões do Modelo de Maturidade

Dimensão	Descrição	Autores
Estratégia	A dimensão estratégia abrange: integração com a estratégia da empresa, roteiro para implementação, gerenciamento estratégico de dados, informações e conhecimento, modelo de negócios voltados para Indústria 4.0.	(Wagire, Anituddha; Joshi, Rohit; Rathore, Ajay; Jain, Rajesh); (Santos, Reginaldo; Martinho, José)
Pessoas e Cultura	Engloba aspectos culturais e organizacionais que envolvem liderança e colaboradores, competências em TIC, inclusão , autonomia, interdisciplinaridade e flexibilização do trabalho.	(Wagire, Anituddha; Joshi, Rohit; Rathore, Ajay; Jain, Rajesh)
Produtos	A dimensão engloba aspectos como: individualidade, flexibilidade e modularidade, desenvolvimento de novos produtos, sistemas embarcados nos produtos e digitalização.	(Santos, Reginaldo; Martinho, José);(Bibby, Lee; Dehe, Benjamin)
Clientes	A dimensão Clientes aborda aspectos relacionados à integração dos clientes aos processos de desenvolvimento e fabricação, integração e utilização de dados, digitalização de serviços e vendas e integração do cliente com ferramentas digitais.	(Pirola, Fabiana; Cimini, Chiara; Pinto, Roberto)
Operações	Aborda tecnologias tais como: modelagem e simulação dos processos, integração vertical e horizontal, digitalização, automação, flexibilidade, autonomia e descentralização. são tecnologias que compõe o processo de transformação do produto, bem como recursos utilizados para integração dos processos.	(Caiado, Rodrigo; Scavarda, Luiz; Gavião, Luiz; Ivson, Paulo; Nascimento, Daniel; Garza-Reyes, Jose)
Governança	Aborda aspectos como: normas trabalhistas, terceirização do trabalho, gerenciamento de dados, políticas de desenvolvimento e inovação, políticas públicas voltadas para o desenvolvimento da Indústria 4.0.	(M. Collia; U. Bergerb; M. Bockholta; O. Madsena; C. Møllera; B. Vejrum Wæhrens)
Tecnologia	A dimensão Tecnologia aborda: utilização de dispositivos móveis, sensores RFID, sistemas embarcados em máquinas e equipamentos, comunicação *machine to machine* (M2M), *cloud computing*.	(Pirola, Fabiana; Cimini, Chiara; Pinto, Roberto);(Rauch, Erwin; Unterhofer, Marco; Rojas, Rafael; Gualtieri, Luca; Woschank, Manuel; Matt, Dominik)

3.2 Definindo os Níveis de Maturidade

Através de pesquisas para estruturação do modelo de maturidade, foi identificado que o modelo CMMI (*Capability Maturity Model Integration*), transformou-se em referência mundial para avaliar a maturidade nas indústrias de diversos segmentos. Para este trabalho, será utilizado o modelo CMMI, onde os níveis representam o status da indústria dentro do contexto da indústria 4.0. Tais níveis variam de 1 (nível baixo) a 5 (nível alto), e são detalhados na Tabela 4 para as dimensões Estratégia, Pessoas e Cultura e também de forma geral, que será apresentada pelo modelo.

Tabela 4. Descrição dos Níveis do Modelo de Maturidade

Dimensão	Descrição do nível de Maturidade
Geral	Nível 1 – Crítico, representa organizações que desconhecem a Indústria 4.0 como novo paradigma industrial Nível 2 – Alerta, significa um conhecimento básico e recente sobre Industria 4.0 Nível 3 – Aceitável, é a organização que já apresenta em fase de experimentação alguma tecnologia relacionada ao novo paradigma Nível 4 – Ótimo, aplica-se as organizações com projetos bem sucedidos com as tecnologias da Indústria 4.0 Nível 5 – Ideal, trata-se de uma organização que utiliza tecnologias da Indústria 4.0 de forma estratégica no negócio e pode ser chamada de organização 4.0
Estratégia	Nível 1. Não existem estratégias para implementação da Indústria 4.0 Nível 2. Estratégias para desenvolvimento da Indústria 4.0 estão sendo desenvolvidas dentro da organização Nível 3. Existem estratégias para o desenvolvimento da Indústria 4.0 em andamento Nível 4. Existe alinhamento entre a estratégia geral da organização e a estratégia voltada para a indústria 4.0 Nível 5. As estratégias da organização são desenvolvidas tendo por base a indústria 4.0
Pessoas e Cultura	Nível 1. A cultura da organização não permite e as pessoas desconhecem a Indústria 4.0 Nível 2. Existem ações planejadas para integração da Indústria 4.0 dentro da cultura da organização e uma preparação das pessoas Nível 3. A cultura da organização permite ações voltadas para Indústria 4.0 e as pessoas estão preparadas Nível 4. A cultura está alinhada com a Indústria 4.0 e as pessoas apoiam as ações Nível 5. A cultura da empresa é voltada para Indústria 4.0 e os colaboradores atuam no desenvolvimento da Indústria 4.0

3.3 Avaliação do Modelo

Para a avaliação do Modelo proposto, optou-se pelo questionário como instrumento para coleta de dados, por suas vantagens em relação aos demais instrumentos. O instrumento de pesquisa proposto, além das características das dimensões, dos níveis de maturidade, será proposto também o questionário para avaliação dos níveis de maturidade em cada dimensão.

Para aplicação do questionário proposto, será necessário aplicá-lo a partir de uma base matemática. Através da revisão de literatura, tendo em vista as dimensões propostas, constatou-se que as dimensões não possuem importância linear, ou seja, as mesmas não são igualmente importante. Desta forma, para determinação dos pesos das dimensões de avaliação, será utilizado o método *Analytic Hierarchy Process* (AHP).

O AHP é uma metodologia de Auxilio Multicritério à Decisão (AMD), que propõe o tratamento de problemas de escolha complexos de forma simples. Este método está baseado em três princípios do pensamento analítico:

- Construção de hierarquias: no AHP o problema de escolha é decomposto em níveis hierárquicos, como forma de buscar uma melhor compreensão e avaliação do mesmo;
- Priorização: o ajuste das prioridades no AHP fundamenta-se na habilidade do ser humano de perceber o relacionamento entre objetos e situações observadas, comparando pares à luz de um determinado foco ou critério (julgamentos paritários);
- Consistência lógica: no AHP é possível avaliar o modelo de priorização construído quanto a sua consistência.

Após a atribuição de pesos às dimensões propostas, será aplicado o método de decisão multicritério baseado em variáveis linguísticas conhecido como 2-tuple. A representação é feita na forma (s, $\propto$), onde s é um rótulo linguístico e $\propto$ é um valor numérico que representa um valor [15]. O método 2-tuple apresenta melhores resultados na modelagem e gerenciamento de incertezas em processos com o uso de palavras [25].

O primeiro passo para a análise dos dados é estabelecer o conjunto de termos linguísticos que serão utilizados no processamento da informação proveniente do questionário. Segundo passo, converter as variáveis linguísticas. Terceiro é identificar as soluções positivas e negativas ideais. Quarto, calcular a distância entre as alternativas até as soluções negativas e positivas ideais. Quinto, é calcular a semelhança com a solução positiva ideal. Sexto, calcular a variável linguística correspondente, com base no passo anterior e por fim, classificar em ordem das variáveis linguísticas. Dessa forma, tem-se os níveis de maturidade das organizações de acordo com cada dimensão proposta.

4 Resultados e Discussão

Este artigo apresentou um modelo de maturidade composto por sete dimensões e cinco níveis de maturidade, destinados a apoiar as organizações de países emergentes em sua transformação digital para a Industria 4.0. Com base nos modelos de maturidade avaliados pelo processo de revisão sistemática de literatura, pode-se notar que nenhum dos modelos contempla a abordagem em países emergentes.

Para atingir o objetivo foi adotado método de decisão multicritério utilizando a abordagem AHP e 2-tuple. No modelo proposto é realizada uma comparação par a par das dimensões estabelecidas e aplicando a ferramenta AHP um peso para cada dimensão é obtido, tendo em vista que graus de importância das dimensões podem variar de acordo com a aplicação do modelo. Por fim esse peso é combinado com a avaliação de cada dimensão e utilizando a ferramenta 2-tuple um ranking é construído e utilizado para determinação do nível de maturidade em cada dimensão proposta.

Por se tratar de um estudo preliminar, não foi realizada a aplicação do modelo proposto. O trabalho futuro irá se concentrar no aprimoramento e validação do modelo de maturidade através da aplicação em organizações, validação dos dados e no desenvolvimento posterior das diretrizes de implantação das ações para o alcance de níveis desejados.

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Developing a Resource-based Manufacturing Process Capability Ontology

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Abstract. This paper addresses the challenge of developing an ontology for manufacturing process capability. This is important task needed to achieve the semantical integration of various manufacturing planning and execution software and hardware (equipment) systems. The research presented has been performed within a framework of Industrial Ontology Foundry (IOF) in which the authors are active participants. Manufacturing process capability is seen as a composition or combination of capabilities and functions of resources participating in the process. Theoretical foundation for the capability composition is presented. Individual participant resource functions are established using axiomatic design principles. The function and capability of the whole manufacturing processes is derived from individual resources using axiomatic design composition of functions. The overall approach is applied on example prismatic parts, their features, and simple machining processes. For each machining process, the machine tool brings one set of functions, while the cutting tool (mill or drill) brings its own functions. When combined for the manufacturing process those functions become capabilities in the whole process. The approach is illustrated on several feature geometries (holes, slots and pockets).

Keywords: First Keyword, Second Keyword, Third Keyword.

1 Introduction

In recent years, researchers envisioned the adoption of cloud computing and service-oriented architectures (SOA) to achieve a high degree of decentralization and flexibility in distributed manufacturing - commonly termed as Cloud Manufacturing (CM). CM is poised to level the manufacturing industry (Igoe & Mota, 2011) by bringing manufacturing resources in reach of inventors, amateur designers, small businesses, and start-ups. CM services (e.g. IaaS, PaaS, and SaaS) aim to virtualize a wide variety of resources: both tangible (hardware, e.g. machine, equipment, server, tools, and material and Software e.g. CAD, CAM, and CAPP) and intangible (e.g. "know-hows", data, standards, employees) (Xu, 2012). Smart Manufacturing in the US and Industry 4.0 in Europe also advocate for the deployment of cyber-physical systems, cloud-based 'servitization' of both tangible and intangible resources, and decentralized production to make production systems autonomous, self-maintainable, adaptive, and flexible (Chituc & Restivo, 2009).

A major challenge in enabling the interoperability of technically disparate manufacturing resources is the inability to codify and integrate manufacturing knowledge. Manufacturing capability is one type of manufacturing knowledge that is not only complex and elusive but to maintain competitiveness different industries have traditionally resorted to developing and protecting their unique capability. Manufacturing capabilities have traditionally been formalized by manufacturers in three forms:

1. machinists' handbooks (Oberg, D. Jones, L. Horton, & H. Ryffel, 2000) and shop-floor manuals - capture the manufacturing knowledge accumulated by the generational experience and experiments.
2. machine and tool vendors - advertise the capabilities of their products (manufacturing resources).
3. technical and mechanical theory - provide scientific (both rule-based and numerical) models for the capabilities of mechanical devices and related processes. Additionally, manufacturing organizations may also advertise their competency in terms of their production performance and quality of the output in a format that is comprehensible and enticing to the targeted customers.

This paper includes - discussion on research new representations of process capabilities, a brief discussion on representing manufacturing systems with ontologies, the presentation of a limited ontology-based process capability model and a case study of how this ontology can represent a representative selection of manufacturing processes.

2 Literature Review

2.1 Process capability in machining

Process capability is defined as historical and scientific knowledge about manufacturing processes (Tien-Chien, Wysk, & Wang, 2006). The authors define three levels of process capabilities: a universal level, a shop level, and a machine level, where the universal level is governed by materials and physics to provide general knowledge about processes (like twist drilling), but other levels focus on true capability within a certain factory or specific machine (drill press or milling machine) which is bound by both physics of the generalized capability and the constraints the machine and tooling providing the capability. For example, the maximum spindle speed of the drill with a certain diameter bit. Important process capability parameters include shape and sized that a process can produce, and dimensions and tolerances that can be produced by various processes. Many manufacturing handbooks contain general capabilities of various manufacturing processes (see for example(Boothroyd, Dewhurst, & Knight, 2010)).

Formal analysis of process capability in research on process planning has been usually done by applying some form of decision rules and/or tables. For example, ref(Wang & Li, 1991) describes detailed reasoning for hole-making operations. Those procedures have been formalized in the research report (Khoshnevis, Tan, & Sormaz, 1993) and implemented in the research process planning system IMPlanner. Details and examples for hole making and milling are provided in (D. N. Sormaz, Khurana, & Wadatkar,

2005) and (D. Sormaz, Gouveia, & Sarkar, 2018). While this approach gives detailed reasoning concerning process capabilities for achieving required dimensions and tolerances, the research on more rigorous formalisms for process capability from first principles has not been covered. For example, the compatibility of various machines, tools, and manufacturing processes is seen as just a binary relation as shown in Fig. 1. For example, milling and drilling tools can be mounted on milling machine, while turning cutters cannot accept milling tools.

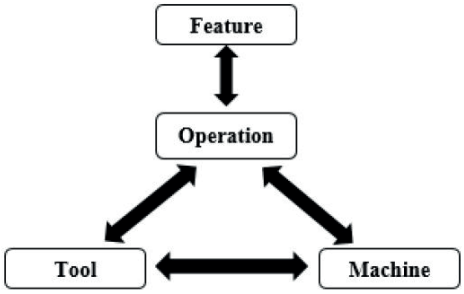


Figure 1. Relations between features, operations, tools, and machines

2.2 Ontologies

Ontologies are structured definitions of real-world entities, their hierarchies, and relationships. An ontology can lay a foundation for an application neutral definition to guide the creation, transformation, and integration of data or knowledge within and across organizations and domains. Creating an ontology demands a thorough examination of the systems being modeled and requires adherence to a rigorous methodology that preserves the philosophical constructs of both the system and the modeling methodology. This development process provides insight into the domain, and the resultant ontology can support data processing, storage, translation, and integration. And the rich and complete representation of a system that an ontology can support, it makes a strong foundation for relational or object-based formats.

While the developer of an ontology should strive to be general and neutral, there will be an implied perspective that the creator (single or group) imparts on their design. Termed as concept orientation, this bias is formed from the creator's perspective and understanding of the system and the ontology methodology being used (Arp, Smith, & Spear, 2015). Couple this bias with breadth and depth bounds imposed by the intended purpose of the ontology and opportunity exists for a design that results in usage limitations. When developing an ontology for manufacturing capability, formalizing existing industry biases will necessarily limit generalization and applicability. Any effort to build such an ontology should respect the three levels of capability of encoding already present – machinist's handbooks, organizational capabilities, and unique machine/tool combinations.

Early attempts to build ontologies for manufacturing domain focused on describing products, manufacturing process, resources, and controls which describe the relations among resources and processes. One early work on the core terms of manufacturing was conducted by Borgo and Leitão, who proposed a set of such core concepts related to manufacturing based on foundation ontology DOLCE (Borgo & Leitão, 2007). The behavior and function of the manufacturing artifacts were developed in their later works (Borgo & Vieu, 2009)(Borgo, Carrara, Vermaas, & Garbacz, 2006)(Borgo, Carrara, & Garbacz, 2010). Although these studies established the functionality of products and resources based on behaviorism and provide some of the conceptual guidelines for understanding capability, they are not exclusively about the manufacturing capability. Another ontology called MASON described by Lemaignan et al. also provided a taxonomy of the core elements of manufacturing, such as process, resources including machine, tool, and raw material but generally lacks entities describing their capability (Lemaignan, Siadat, Dantan, & Semenenko, 2006).

Ameri et al. developed an ontological model describing manufacturing processes and resources as services, which included a detailed study on the capability of machine and tool (Ameri, Urbanovsky, & McArthur, 2012). They also conducted a thesaurus-guided discovery of capability related terms (Sabbagh, Ameri, & Yoder, 2018) as well as developed a process and resource selection module leveraging the capability knowledge (Ameri, 2013). Lu et al. (Lu, Shao, Singh, Xu, & Ye, 2014) developed a taxonomic representation of manufacturing process and resource capabilities directly translating concepts from STEP-NC (ISO) standards using the OntoSTEP methodology proposed by Barbau and Krima (Krima, Barbau, Fiorentini, Sudarsan, & Sriram, 2009). Luo et al. developed a DL based language called MCDL, which utilized the fuzzy-DL concepts in modeling capability ranges for manufacturing resources (Luo et al., 2013). In a recent publication, Järvenpää et al. described a new ontological model for manufacturing capability, named MaRCo (Järvenpää, Siltala, Hylli, & Lanz, 2019), which supports capability matchmaking for resource discovery.

The recent development in the ontology application is Industrial Ontology Foundry (IOF) [ref iof web site]. This effort is based on developing the industrial ontology framework that enables seamless data integration base din semantic marking of data from various applications (such as PLM, ERP, MEs, and others). The framework is based on the adoption of the Basic Formal Ontology (BFO)[1] and layered development of industrial ontologies. The initial effort was devoted to building core common terms for all industrial applications (Smith et al., 2019) and the current work is in developing modules for process planning, supply chain, maintenance, and few other areas. The authors of this paper are active participants in the IOF activities and this work is being done in the IOF framework.

[1] https://github.com/BFO-ontology/BFO

3 Manufacturing Resource and Process Capabilities Model

3.1 Capability of a resource

Colloquially, the term 'capability' is used in describing the ability of some object to achieve a goal. In manufacturing, objects may be items like consumable or capital resources, e.g. material, machine, tool, fixture, die, mold, vehicles, or non-consumable assets, e.g. land, building, and workers. It is also apparent that the capabilities of a resource or asset can only be described in a particular context, which is composed of two different conditions: there must be a method or process in which the object is to be used and there must be a purpose which is expected to be fulfilled. This observation is demonstrated from the following descriptions of capability.

1. An LED light bulb can provide more brightness but consume less energy than a CFL.
2. The two pentalobe screws located on the bottom of an iPhone 6 can be unscrewed by a 5-point pentalobe screwdriver.
3. A robotic hand can pick and remove defective parts from an assembly line.

The notion of the capability bears a phenomenological aspect as some capabilities of an artifact manifest in the context of some benefit which some agent intends to derive from the realization of that capability.

Premise : For every c as Capability, when realized in a Process p, some purpose (of an agent) is fulfilled or some intention is realized (of an agent).

Several analyses resort to behaviorism and model this aspect of capability as a behavior of an artifact, ranging from radical stances such as explaining the outcome or trait of an artifact based on its responses caused by some external stimuli interacting with the internal structural state of the artifact to a more teleological interpretation by avoiding to use the internal causal factors of the artifact in the explanation for the behavior of the artifact in a certain process but posit it as an outcome of the process.
Despite the rigor, radical behaviorism faces hurdles when used in practical situations, some of which are discussed in the publication (Sarkar & Šormaz, 2019). In this paper, 'capability' is classified as a type of 'disposition' (Spear, Ceusters, & Smith, 2016). Being a subtype of disposition, any instance of capability is by default a realizable entity, which is realized when putting in a specific situation ("special physical circumstances," – BFO). This situation-specific realization, which in a way captures the modal aspect of behavioral tendencies of artifacts, covers premise 1.

We further define capability of the manufacturing resource in terms of the function of the resource. The term 'function', as defined in BFO, contains the basis of etiological

selection or artificial creation (Spear, Ceusters, & Smith, 2016), that what the artifact is capable to do is the original purpose of the artifact's existence.

This normative purpose (and the original intention) of an artifact is encapsulated in the functional property of that artifact. Therefore, the premise 2 can be rewritten by using the term function as 'For every c as Capability, when realized in a Process p, some function f, that inheres in the bearer of c, is also realized'.

The restatement also assumes the premise that for a capability to be realized, the bearing artifact must participate in a process. This is because capability, being a realizable entity (BFO), can only be realized in a process, of which the bearer object is a participant. Furthermore, the function being a normative purpose of the artifact (Spear et al., 2016), it must be the case that the process, which realizes that function, occurs in a prescribed manner.

In an aim to derive an OWL-friendly definition (Def. 1) for capability, we introduce a new relationship appraises, which is further axiomatized below.

Axiom1:$Capability(c) \equiv Disposition(c) \wedge \exists f\ appraises(c, f) \wedge (Function(f) \vee Role(f))$

Axiom 2: $appraises(c,f) \rightarrow \exists p, \forall o\ inheresIn(c,o) \wedge inheresIn(f,o) \wedge participatesIn(o,p) \wedge realizes(p,c) \rightarrow realizes(p,f)$

The definition given in Axiom 1 restricts the range of relationship appraises to be either function or role. The reason for including the role in the definition is two fold. Although this paper focuses only on the capability of manufacturing resources, such as machines and tools, which are classified under 'material artifact' in BFO, human beings, such as artisans, operators, and workers, and collectives, such as manufacturers, land, and organization, also possess the capability. However, upon being realized in some manufacturing activity, the capabilities do not necessarily realize any function of these agents as it is debatable in the first place that agents can bear such function (abilities are not functions as most of them are acquired in a lifetime of an agent and thus not etiologically selected. They are also not engineered as the physical structure bearing the capability is not modified while acquiring that capability (Merrel, Limbaugh, Anderson, & Smith, 2019)). to another question: which way is the realization of a capability different from the corresponding realization of a function? It is necessary to disseminate the implication 'realizes(p,c)→realizes(p,f)' further. Functions are always end-directed, that one must find the world in a specific state if they are realized in a process. On the other hand, when some capability is realized, the bearing artifact or some other object, which also participate in process p, is expected to be in a certain state(s). What we broadly mean by the statement 'capability appraises function' is that capability demarcates or predicts the extent by which some function is realized. To be specific, the process, which realizes both the capability and the function, brings forth some state of the world which is commonly contained by the state descriptions associated with both.

However, the capability of a resource is always graded, that it is expressed as a range of expected outcomes. It is thus necessary for the predicted range of the capability to

be such that it overlaps the set of outcomes specified by the function either completely or partially. For example, a lightbulb being capable of producing warmer color temperature (e.g. there are instances of it producing a color temperature of 2700–3000 K in some occurrences of glowing) implies that the light bulb is suitable for making a room cozy (e.g. it has a function of keeping the color temperature of the room at around 2800K). Based on the above evidence one may follow Axiom 1 to say that the capability of producing warmer color temperature appraises the function of making the room cozy.
In a an earlier work (Sarkar & Šormaz, 2019), we presented a formal axiom to capture this granular notion of capability being realized in a process based on fluent, considering that the state description for the function and the capability, which appraises (labeled as demarcates) the function, is a quality measurement and a set of tolerance limit for that measurement In practical application, this exposition based on the process-specific behavior of resources is not necessary to talk about the function or capability of resources. Furthermore, the first-order axioms cannot express the function of a system based on its process-specific behavior completely as it is not expressive enough to capture the modality imbued in such models. On the other hand, the teleological approach adopted in Axiom 1 is more straightforward: "A resource has a function by virtue of its capability."

3.2 Capability of a system

In the modern manufacturing industry, most operations are conducted on complex systems integrating several types of machines, tools, and equipment. Functional decomposition is a popular reductionist strategy, adopted for modeling complex systems by engineers. This method aims to decompose a higher-order function into sub-functions in such a way that if every such sub-functions is realized then the higher-level function is also realized. One of the utilities of functional decomposition is system design, which is to find a suitable mereological hierarchy of subsystems, assembly, and components, that can be assembled into a complete system, capable of achieving such function. This method is also applied in modeling the system architecture as a logical sequence of the functions, which is commonly recorded as a functional flow block diagram in system analysis (US Department of Defense Systems Management College, 2001).

The aggregation among sub-functions mirrors the interdependency of functions as described by Kitamura and Mizoguchi: "A function is achieved by performing(achieving) a series of sub-functions which is called a method of function achievement" (Suh, 1998). In their model, the judgment for the realization an upper-level function in a process is derived from comparing the behavior displayed by the system, due to the underlying structure of the system or its component, to the behavior, expected by the function. The crux of this idea is derived from the FBS ontology of Gero (Gero, 1990). However, modeling functional decomposition based on process-specific behavior of systems and its components is not trivial as such causal-interaction is often emergent and greatly influenced by the experience of the observer.

Axiomatic design (AD) theory, developed by Nam P. Suh, is an integrated model that can be applied in both system design and analysis. AD uses the functional decomposition method in mapping a set of objectives to solution space. By applying the transformation iteratively, more details of the solution unfold, ultimately generating a mereological hierarchy of the complete system (Suh, 1998). AD fits perfectly with the teleological basis of the function we adopted in our definition of capability as it can help in axiomatizing the linear mappings (design matrix) among a set of objectives (functional requirements) and a set of solutions (design parameters of a system). To illustrate the method, the case in example 3 is modeled with AD by constructing the transformation matrix from the capability matchmaking.

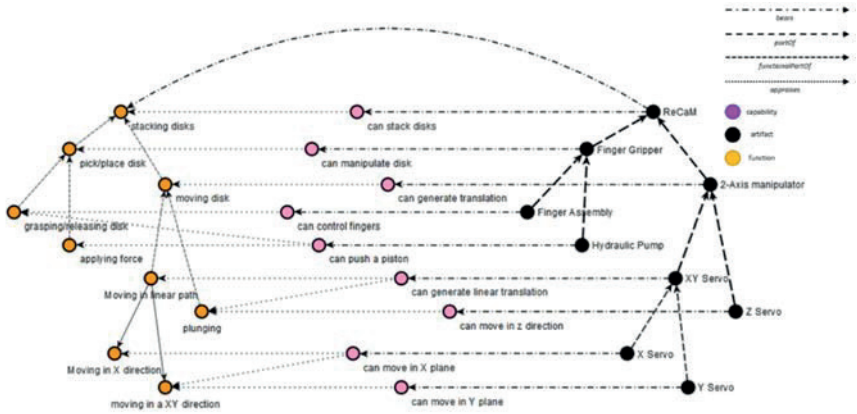


Figure 2 Axiomatic Design principle applied to derive the structural decomposition of a robotic hand which can fulfil the functional requirement of stacking disk on a pallet by collecting them from a conveyor belt.

The term function used in the definition of capability is based on teleological sense and deviate from the behavioral perspective, adopted in DOLCE (Borgo et al., 2006) and YAMATO (Kitamura & Mizoguchi, 2004). However, the teleological interpretation of function is useful in describing the concept of functional decomposition as every sub-function plays some role in achieving the end-goal prophesied by the parent function. We define the relation decomposition based on the result of the process in which these functions are realized without assuming any parthood among its bearers. Although AD links components of a system to the sub-functions, not all types of parthood are described along the functional line.

Axiom 3: $\forall f,\ f' decompose(f', f) \rightarrow \exists f_1 f_2 \dots f_n\ \wedge_{i=1}^{n} decompose(f_i, f) \wedge f' \in list(f_1, f_2, \dots f_n) \wedge \exists p p_1 p_2 \dots p_n realizes(p,\ f) \wedge \wedge_{i=1}^{n} realizes(p_i, f_i) \rightarrow \exists o o_x p_x achieves(p, o) \wedge achieves(p_x, o_x) \wedge o_x = o \wedge generalOccurrentSumOf\left(p_x, list(p_1, p_2, \dots p_n)\right)$

Axiom 3 states that for every function, that decomposes another function, is a member of a list of functions such that if all functions in the set are realized then the parent function is also realized. This implies that the objective (state description(s)) achieved by the process that realizes the parent function is the same as the objective achieved by the general composition of the processes that realize the sub-functions. It is to be noted that 'list' is a function (not to confuse with the term 'function') which returns a list of the elements given as input. The relationship '*generalSumOf*' holds between the general mereological sum of some occurrents and a list of those occurrents.

In Figure 2, the primary function of "stacking disk" is realized when two sub-functions "pick/place disk" and "moving disk" is realized. These sub-functions are realized only when processes, such as picking, placing, and moving, occur in a suitable order or in parallel. In other words, the combined effect of these processes results in a disk being stacked.

In the AD method, a design matrix maps the vector of functional requirements to a vector of design parameters, which are components of the purported system that bears the parent function. Each element of the matrix denotes the extent in which a function is 'satisfied' (as a requirement) by a component, that if greater than 0 then the component may bear that function. For example, the vector of functions In Figure 1, i.e. {'manipulating disk','moving disk'}, can be mapped to the vector of components, I.e. {'finger gripper','CNC'} using the design matrix A, as,

$$\begin{Bmatrix} 'manipulating\ \text{disk}' \\ 'moving\ \text{disk}' \end{Bmatrix} = A \begin{Bmatrix} 'finger\ gripper' \\ 'CNC' \end{Bmatrix}, where\ A = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix}$$
$$, X\ \text{being a non} - \text{zero number greater than 0.}$$

However, not every design matrix yields in a valid design as AD dictates that the independence of sub-functions is ensured by using a design matrix which is either diagonal or triangular (Suh, 1998). Before axiomatizing the independence axiom, a special parthood relationship among components of a system is given in Axiom 4 based on the functions they bear. This relationship, *functionalPartOf*, is a sub-property of proper parthood but only holds between the parent and child components only when at least one function inhering in the child component decompose some function inhering in the parent component.

Axiom 4: $FunctionalPartOf(a', a) \rightarrow ContinuantPartOf(a', a) \wedge \exists f f' inheresIn(f, a) \wedge inheresIn(f', a') \wedge decompose(f', f)$

The independence axiom of AD requires that the list of sub-functions, which decomposes a parent function, should contain the minimum number of independent functions necessary to satisfy the parent requirement: "each one of the functional requirements can be satisfied without affecting the other functional requirement" (Suh, 1998). Therefore, it is not guaranteed that every system containing some components as its functional part is a valid assembly. AD prescribes that the design matrix must be either diagonal or triangular to satisfy the independence axiom. Before we can add that

constraint in an ontology, we need to formulate a scheme to derive the matrix on the logical consequence.

As we exposited in the previous section that a function of an artifact exists in virtue of the artifact's capability. For manufacturing resources, they are primarily designed and built to have certain capabilities. Therefore, a resource is suitable for achieving a functional requirement only when it has some capability that appraises such capability. The design matrix then can be formulated as

$$A = \{Aij = 0..1 \wedge \mathbb{I}|1: \exists c\ inheresIn(a_i, c) \wedge appraises(c, f_i), 0: otherwise\}$$

Based on this definition, for aggregation of components is valid only when every component has some capability which either appraises a capability independently without any other capability also appraising the processor along with another capability that again appraises another sub-function independently. We can classify the capabilities in this line as independent capability and enabled capability. An enabled capability is a capability that is enabled by either some independent capabilities or enabled capabilities. An enabled capability that enables another enabled capability cannot be enabled by that capability it enables. Therefore, the relationship *enable*, given in Axiom 5, is transitive, non-reflexive, and anti-symmetric.

Axiom 5: $enable(ci,cj) \rightarrow \exists fi\ \ appraises(cj,fi) \wedge appraises(ci,fi) \rightarrow \exists fofj\ decompose(fi,fo) \wedge decompose(fj,fo) \wedge appraises(ci,fj) \wedge \neg appraises(cj,fj)$

4 Case Study

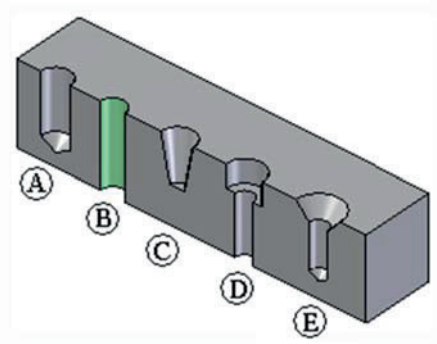
The illustration of a capability ontology will be illustrated on building ontologies for the case of machining prismatic features. Most discrete manufacturing industries have parts of generally prismatic shape (usually produced on milling and drilling machine tools) with so-called prismatic features as components of the part design (shape). Most common features are either direct or derived from holes, slots, and pockets (J. J. Shah & Rogers, 1988) (J. Shah & Mantyla, 1995) which, when combined generate a variety of complex shapes. The features and their attributes form the functional requirement for the machine-tool selection. As explained in the earlier sections, machining systems capable of satisfying these functional requirements should have some capability that can appraise the corresponding functions (no distinctions between function and its requirement is made in this study). In Table 1, some of the typical form features and required capabilities of the machine are given.

Obtaining a certain feature is all dependent on a combination of several factors such as a method of tool entry, the primary cutting motion of spindle, and the direction of cutting. For example, a small hole requires plunging, the rotational motion of the spindle, and axial cutting. Following the AD method, a suitable machine should have some components which bear these capabilities individually. However, the overall requirement also needs to be decomposed to deduce the correct assembly and combination of

these components. In most of the CNC machining, a suitable tool is also required. In this study, we only focus on drill bits, which are used for making a hole.

Table 1 Machining Features

	Feature	Method of Tool Entry	Primary Cutting Motion (feed) of Spindle	The Direction of Cutting
	Closed pocket	Ramping	XY path	Radial Cutting
	Large hole (circular pocket)	Helical interpolation	Circular XY	Radial Cutting
	small hole	Plunging	Rotation	Axial Cutting
	Slot	Ramping	X or Y	Radial Cutting



A. Simple hole
B. Threaded hole
C. Tapered hole
D. Counterbore
E. Countersink

Figure 3. Common hole types[2]

The type of drill bit you need typically depends on the type of hole being created. For example, a counterbore hole - Round bottom requires a step drill and a round bottom profile as given in Table 2.

[2] http://www.soliddna.com/SEHelp/ST6/EN/feature_modeling/feat11c.htm

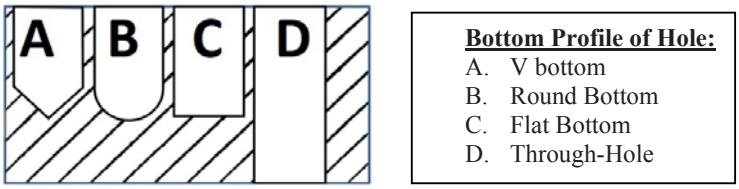


Figure 4 Common types of hole bottoms

Table 2 Matching between holes and drilling tools

Side Profile	Type of drill bit	Bottom Profile of hole
Simple Hole-Round Bottom	Conventional/Spur/Spade	B
Simple holes- Flat bottom	Conventional/Spur/Spade	C
Simple holes- V bottom	Conventional/Spur/Spade	A
Counterbore holes- Flat bottom	Counterbore	C
Counterbore holes- Round Bottom	Step Drill	B
Counterbore holes- V bottom	Counterbore	A
Countersink- Flat bottom	Countersink	C
Countersink- Round bottom	Countersink	B
Countersink- V bottom	Countersink	A
Threaded holes- Flat bottom	Tap Drill	C
Threaded holes- Round bottom	Tap Drill	B
Threaded holes- V bottom	Tap Drill	A

The decomposition of function 'drilling small hole' is given in the diagram shown in Figure 5. The parthood among the corresponding CNC drill machine and a drill bit is also shown. The capabilities presented in figure 5 present the ability of a machine/tool combination to produce the defined hole feature.

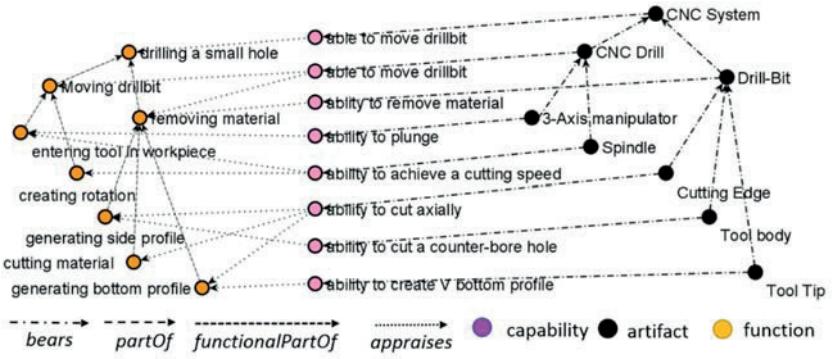


Figure 5. Relations between resources, functions, and capabilities

The OWL file contains a list of rules which capture the knowledge of what type of capability appraises what type of function (see Figure 6). Other rules implement the axioms given in the previous section in description logic-friendly way.

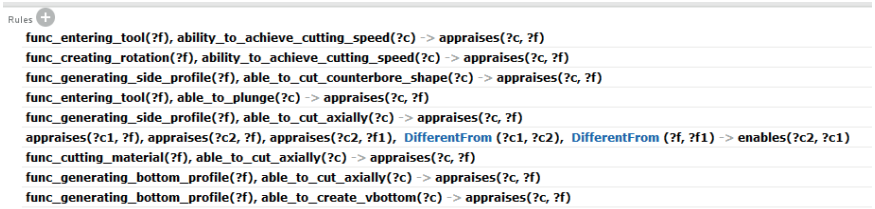


Figure 6. Relation definitions as part of ontology in OWL file

The hierarchy is automatically verified by running reasoner (Pellet) in Protégé. The result of *enable* property assertions are shown in the Figure 7.



Figure 7. Results of the reasoner processing in OWL

5 Conclusions

In this study, we described the manufacturing resource capability as the evaluator of its function. Based on this concept, we derived a logical method to model a machining system by combining suitably capable components, which satisfies the overall function by satisfying the sub-functions. The major contribution of this study is to derive relationships based on the independence axiom of AD. A case study is also conducted to show that suitable CNC machining systems for generating prismatic form features of a part design can be built based on primitive capabilities of machine components and tools. There can be a variety of tools and machine which has similar capabilities. The appraises relationship can be deduced based on numerical ranges. In that sense, many alternative machine and tool combinations may be derived. For finding the best system design, the second axiom of AD, called the information axiom, should be applied. Also, the functional decomposition shown in the case study does not consider the flow of material, energy, and information. These flows are useful for designing the connections among the components. The information axiom and the flow among functions are not covered in this study and will be addressed in a future effort.

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Process Plan Reasoning based on SPARQL Extension

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Abstract. Industry 4.0, Smart Manufacturing, and Digital Twin are technologies that penetrate modern companies in various industries, from automotive, to aerospace, and further to food, chemical, and oil and gas industries. Ubiquitous nature of digital data about variety of processes, the use vast range of software system pose a significant problem for efficient operations. The need to share the data requires that the data are uniformly understood by those software products. This paper presents the result of achieving semantic data integration between product design and manufacturing based on manufacturing process planning ontology as canonical model. First, we present the framework for semantic knowledge in process planning that includes manufacturing features, their tolerance requirements, precedence between them, and necessary processes for their completion. This semantic knowledge has been organized into a manufacturing planning ontology SIMPOM. From the given ontology process planning is executed by developing SPARQL queries, which match the feature requirements with process capabilities and select appropriate processes for each feature. Depending on requirements one or more processes are needed for each feature. The reasoning process in the second phase, also using SPQRQL, includes generation of possible sequences of those processes with consideration of necessary precedences. The process is illustrated of few common features in prismatic parts (holes and slots) and then applied few industrial parts with satisfactory results.

Keywords: process planning, ontologies, SPARQL

1 Introduction

According to Groover [1], "Process planning consists of determining the most appropriate manufacturing and assembly 'processes' and the sequence in which they should be accomplished to produce a given part or product according to the specifications set forth in the product design." In recent times, growing trend in decentralized manufacturing demands that such planning to be conducted by considering distributed manufacturing vendors and partners, where there capability is not known beforehand. Semantically tagged linked data may prove beneficial in integrating the manufacturing processes they can perform and range

of capability of various machining resources they posses. In the past, a number of ontology models were proposed for capturing product design and manufacturing process related information - some of which are given in section 2. These researches build the supporting environment for such distributed planning but any effort to select suitable processes and deduce ordering among the processes for a given product design by using pure logical reasoning is not known to the authors at the time of writing.

As the primary focus of this paper, a set of axioms is designed to represent manufacturing process planning as totally ordered instances of process. Next, we use the proposed semantics in a set of SPARQL queries which can actually build all possible alternative machine routing (a total ordered sequence of occurrences of process instances) from a given part design. In Section 3 we present the ontology for capturing and validating these alternative routes. In order to generate these routes, the queries are executed using a framework which helps them to be executed individually, in a group, once or perpetually until failure. The framework is not part of this paper, which presents three main queries in Section 4 to briefly describe the way a tree-like linked data is generated, which captures every possible routes for each feature of a part design and thus represents the entire process plan as an integrated structure carrying both design and production elements.

2 Literature Review

Utilization of ontology for knowledge based process planning slowly gained the attention of researchers around mid-2000. Two of the notable early knowledge modeling efforts are: foundation of core ontology in manufacturing by Borgo and Leião [2] and formalization of product life cycle semantics (PSRL) by Patil et al. [3]. Since then, a number of manufacturing ontology were proposed, for capturing both upper level and domain specific manufacturing concepts. ADACOR is developed based on DOLCE to facilitate a holonic manufacturing platform [2]. Open assembly model (OAM) proposed by NIST [4] for capturing product design including components and assembly. OAM extends object-oriented Core Product Model (CPM), an earlier model proposed by NIST [5].

In an attempt to provide semantics to STEP standards, ONTOStep provided an ontology to map the STEP functions in OWL model [6]. ONTO-PDM is an ontology developed based on STEP PDM to define fine-grained knowledge structure for product assembly, bill-of-material, and material types [7].

One of the early works on the core terms of manufacturing resources and their capabilities was conducted by Borgo and Leitão based on foundation ontology DOLCE [8]. The behavior and function of the manufacturing artifacts were elucidated in their later works [9,10,11]. MASON ontology proposed by Lemaignan et al. tried to capture the precedence relationship among different manufacturing operations required to produce a part with the desired quality [12]. Assembly Relation Model (ARM) proposed by Kim et al. describes a number of widely used assembly processes, such as joining, bonding, riveting, welding,

and their sub-processes [13]. Ameri et al. [14] developed an ontological model describing manufacturing processes and resources as services, which included a detailed study on the capability of machine and tool. Lu et al. [15] developed a taxonomic representation of manufacturing processes and resource capabilities, by directly translating concepts from STEP-NC (ISO) standards, using the OntoSTEP methodology, proposed by Barbau and Krima [6]. Luo et al. developed a DL based language called MCDL, which utilized the fuzzy-DL concepts in modeling capability ranges for manufacturing resources [16]. In a recent publication, Järvenpää et al. described a new ontological model for manufacturing capability, named MaRCo [17], which supports capability match-making for resource discovery.

Early knowledge-based CAPP systems remain a popular branch of CAPP research since the 1980s. Several CAPP systems, e.g. GARI by Descotte and Latombe [18], EXCAP by Davis and Darbyshire, SIPP by Nau and Chang, and XPLAN by Lenau and Alting, all of which were developed in the early 90s, can be classified as knowledge based expert system (KBES). A framework of data integration of CAD, CAM, CAPP, NC and MRP systems was developed by Dhamija et al., based on Unified Data Meta Model (UDMM) [19].

A long-standing research in knowledge-based CAPP was initiated by Sormaz and Khosnevis[20,21], which followed some forebearing works, such as HiMapp [22] and RTCAPP [23]. HiMapp uses a revised form of a planner called 'Deviser' in its core. RTCAPP consists of frame representation of knowledge, connecting processes, machines, and tools, and a cost based system for concurrent part and process design[24]. Advancing on these early works on knowledge-based process planning Sormaz et al. addressed the technologies necessary to achieve distributed, integrative product configuration and mass customization, such as knowledge engineering, alternative process selection, visualization of decision space, product, and process by XML-based data exchange [25]. The foundation of these developments was a 3D planning model which integrates aggregation, time and variety, which guided the process selection and ordering.

In this study, the process planning concepts and related class and properties are discussed based on a product design ontology and process capability ontology; both of which were developed in our earlier studies [26,27], based on basic formal ontology (BFO) [28] (ISO/IEC DIS 21838-2) as top level ontology. every class and property, used in the axioms, contains an IRI. Separate IRIs are used to distinguish among concepts for design, process, resources, and planning. Moreover, the classes and relationships of these ontology are inherited from bfo and common core ontology (cco) which can be found at https://github.com/CommonCoreOntology/CommonCoreOntologies. In this section and nexts, the classes and properties bear their respective IRI, which we represent by prefixes.

3 Semantic knowledge of process plan

A process plan is essentially a collection of planned processes (instance of `PlannedProcess`). The process plan may be defined by adopting the 'temporal parthood' among processes, following the sub-activity relationship of PSL [29]. Based on the aggregation axis of three-dimensional process plan model [21], many different ways of aggregating processes in a process plan are formally defined in [30]. In this study, the machine, tool, and setup based aggregations are ignored, as our primary goal is to define the ordering among the leaf activities of the activity tree (borrowed from PSL [29]).

The precedence relationship among the instances (occurrence) of a process (universal process type or an activity) is the basis of the 'occurrence tree' in PSL [29]. Every node of an occurrence tree is the primitive or atomic activity occurrence, which are occurrences of the activities at the leaf nodes (which are not decomposed further into sub-activities) of the activity composition hierarchy. Every occurrence in the tree denotes a single step in a possible routing. Therefore every path from the root to leaf occurrence of the occurrence tree provides a possible routing.

As the first criteria for an occurrence to be part of a valid route is that the occurrence should be able to satisfy some of the specification associated with the given design. Following our earlier work [31] on specification-capability matching as a method of evaluating the suitability of a process, we appropriated the *legal* predicate from PSL to state that every occurrence (o) is a member of the occurrence tree ($\mathcal{O}$) if process has some capability which satisfy (function `doesMatch`) any specification associated with some features of a part design (Axiom 1).

Axiom 1 $\forall o, \mathcal{O}\ o \in \mathcal{O} \rightarrow \exists f_s\ f\ q_s\ q\ p\ c\ hasSpecification(f_s, q_s) \wedge occurrenceOf(o, p) \wedge hasCapability(p, c) \wedge inheresIn(q, f) \wedge ((doesMatch(c, q_s) = q) \rightarrow concretizes(q, q_s))$

Next, two types of precedence constraints govern the validity of a process plan. The first one stems from the processing order among features of a part, and the second one from the type of processes to be applied for producing a feature.

Features (e.g. Hole, Slot, Pocket, Chamfers, and Bevel) in product design can only be machined in a specific order due to their overlapping spatial location (position) and orientation (vector) [32]. In general, this type of precedence constraints is imposed by design specification, such as the dimension datum reference and tolerances. In Axiom 2, *psl:minPrecedes* (variant of *psl:successor*) relationship among two occurrences when the activity of the first occurrence is meant to *achieve* (proposed relationship following fluent notion) some quality improvement in a feature, which should be processed before (expressed by using *nextFeature* relationship among features) the feature to be handled by the second occurrence.

Axiom 2 $\forall o, o_s, o'_s minPrecedes(o_s, o'_s, o) \rightarrow \exists a, a_s, a'_s, f, f'$
$occurrenceOf(o, a) \wedge occurrenceOf(o_s, a_s) \wedge occurrenceOf(o'_s, a'_s) \wedge$
$achieves(a_s, partOf(p, f) \wedge achieves(a'_s, partOf(p, f') \wedge nextFeature(f, f')$

Similar to the precedence among features of the part, a valid process plan also needs to follow a particular ordering for the processes applied in order to make one feature meeting its specification. This sort of situation is normal for CNC machining, in which more than one machining step may be required in order to make the product feature in order to meet tolerance specification such as dimension, tolerance, and surface finish. The precedence among processes is best handled if an intermediate object is generated for every step. Following this approach, we may generate intermediate features for the part design whenever more than one process is required to satisfy the specified tolerance requirements. In Figure 1, the precedence among its four features, given in the left graph, is extended by accommodating intermediate features in the graph on the right. The corresponding activity hierarchy is generated by first aggregating the complete plan for the part by machine, then setup, then features, and by step activities in the end, each of which generates one of the intermediate feature. For this particular case it can be stated that to make the feature 'Slab1' we need only milling process ('Step1'), while for the other three features we need two processes for each: for Hole we need twist drilling ('Step3') and boring ('Step3i'), for Slot we need rough ('Step4') and finish ('Step4i') milling operations.

In this particular case, when applied as subactivity of the same `FeatureAct3`, twist drilling (`Step3i`) should precede boring (`Step3`), which can be stated as $\forall \mathtt{o_b} occurrenceOf(\mathtt{o_b}, \text{`}\mathtt{Step3}'\text{)} \wedge legal(\mathtt{o_b}) \rightarrow \exists \mathtt{o_t}, \mathtt{o}\ occurrenceOf(\mathtt{o_t}, \text{`}\mathtt{Step3i}'\text{)} \wedge$ $occurrenceOf(\mathtt{o}, \mathtt{FeatureAct3}) \wedge nextSubocc(\mathtt{o_b}, \mathtt{o_t}, \mathtt{o})$.

It is apparent that without any constraint on the sequence of the steps, every branch of the occurrence tree is a viable route, or in other words, a possible plan for the part. The portion of the occurrence tree, given in Figure 2, is built by considering the feature activities in the activity hierarchy as the atomic activities. It is to be noticed that, only three routes, which are marked by green, are valid routes as per the original feature precedence network, given in the graph in Figure 1.

4 Methodology

The ontological theory presented above may be used to reason over an occurrence tree already built. First the set of occurrences, which satisfy the Axiom 1 may be selected and then the precedence relationship among them may be computed by evaluating constraints arising from feature and process precedence. It is not effective to run reasoner to validate enormous number of combinations of such process occurrences. In stead, a set of SPARQL queries are written by closely following the axioms. These queries run in iterations to gradually build the occurrence tree by only possible occurrences of processes by following the given precedence among features, and then processes, each time also evaluating

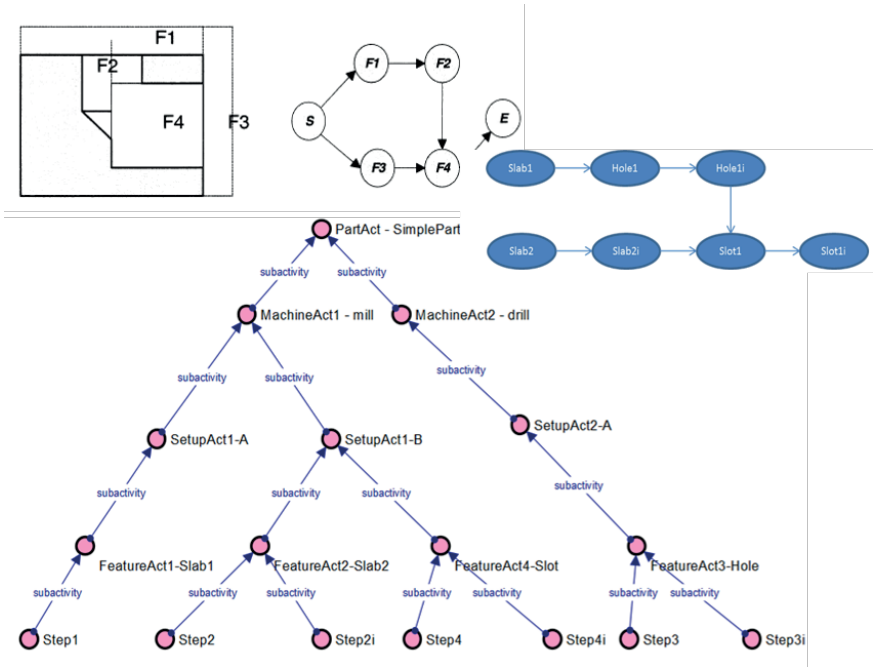

Fig. 1. Extended FPN of a simple part with four features.

whether such process is capable of satisfying any remaining specifications for the work-in-progress part.

The particular type of SPARQL query, used in this study, contains CONSTRUCT clause with one or more unknown variables. These variables are mapped by invocation of a associated service (given in additional FUNCTION clause), which may trigger another SPARQL query before returning values. Such type of augmented SPARQL is used to distribute the planning into different query engines using service based communication. As the rest of the patterns in these queries strictly follow the standard SPARQL 2.0, this particular augmentation is not discussed in detail in this paper.

The entire planning system contains many such SPARQL queries but only three of them are presented below. The first query builds the occurrence tree for the entire part, following the precedence among its features, the second query builds the sub occurrence tree for each feature, following the prescribed sequences of alternative processes, and the third query shows a sample strategy of matching specification and capability. Other SPARQL queries are mostly used for utility purposes, such as importing initial triple sets, transforming local RDF knowledge base, and updating the triple set for query answering.

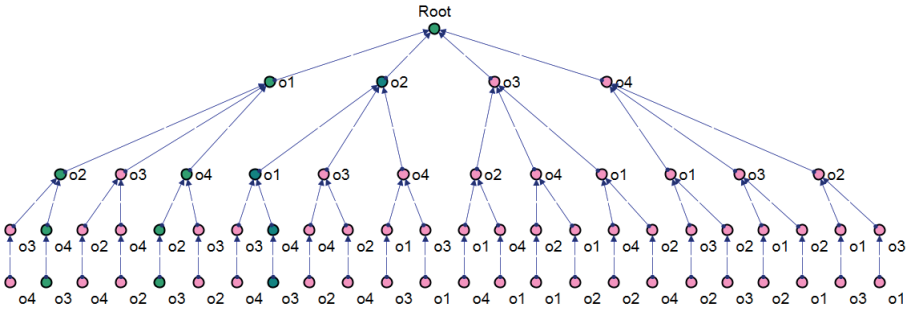

Fig. 2. Occurrence tree for the simple part shown in Figure 1.

4.1 Plan Feature by Precedence

Before the query 'plan-features-by-precedence.rq' (Figure 3) is triggered perpetually until there remains no feature to be planned, or in other words, the select query fails to return any value, the root of the occurrence tree, which is a dummy occurrence of type `plan:RootProcess`.

At each iteration, the SELECT query selects the next available set of feature specifications for each routing so far planned. Five nested SELECT queries, which forms the WHERE clause of the main query, finds all possible features which can be planned for each routing planned so far and filters them for various criteria, such as no such feature be already processed by some occurrence in the corresponding routing. Finally, the FILTER clause at line 26-27 filters only those pairs, bound in ?pCurrent (last occurrence for every routing) and ?rNext (next available feature representations to be planned), for which the count in ?frcount (number of distinct features should be processed as per feature precedence) is greater than or equal to the count in ?fpcount (number of features already processed by the routing).

This particular pattern, consisting of line 21-25, is a ubiquitous pattern, which is used in many rules to find the leaf node of a tree, starting from the root node. In this case, the pattern binds the leaf occurrences to the variable ?pCurrent. Once the leaf occurrences are identified, every possible routing can be found by traversing the path from leaf occurrence to the root occurrence. This is performed by employing the inverse property path ^plan:precedes* (zero or more), which binds all the occurrences in ?p3 for each routing, the last occurrence for which is denoted by each occurrence in ?pCurrrent.

The service is selected automatically by the query by matching the type of the feature specification instance with the input type of the service. The service selects a set of routes, each of which can process the feature completely. These routes can be represented by a occurrence tree. This occurrence tree forms a portion of the complete occurrence tree; therefore, can be called sub-occurrence tree, representing the alternaitve routes for a feature. Every 'feature planning' service returns the set of nodes, which are the direct children of the root oc-

currence of the sub-occurrence tree. On successful execution of the service, the CONSTRUCT part of the rule 'plan-features-by-precedence.rq' appends the returned list of occurrences as children (*plan:precedes*) of the current leaf processes of the current occurrence tree. The leaf occurrences are those, which are bound to ?pCurrent for the input feature specification in ?fs.

```
PREFIX  fpsel:  <http://www.ohio.edu/services/featureplanning/>

CONSTRUCT{?pCurrent    plan:precedes     ?pNext.}
WHERE{?fs cco:represents    ?fNext;
    cco:inheres_in/rdf:type/cco:has_text_value      ?fn;
    cco:inheres_in/rdf:type/cco:has_URI_value         ?ft.
    {SELECT ?pCurrent ?fNext ?rpCount (count (distinct ?r5) as ?r5Count)
      WHERE{?pCurrent  ^plan:precedes*  ?p5.
      ?p5  cco:has_output/^cco:specified_by  ?r5.
      ?fNext  ^plan:hasSucceedingFeature  ?r5.
      {SELECT ?pCurrent ?fNext (count (distinct ?rp) as ?rpCount)
        WHERE{
           ?fNext      ^plan:hasSucceedingFeature      ?rp.
          {SELECT ?pCurrent ?fNext
            WHERE{
              ?pCurrent   ^plan:precedes*                ?p3.
              ?p3        cco:has_output/^cco:specified_by  ?r3.
              ?r3        plan:hasSucceedingFeature      ?fNext.
              {SELECT ?pCurrent ?rc
                WHERE{
                    ?p0        rdf:type         plan:RootProcess.
                    ?p0        rdf:type         plan:PlannedProcess.
                    ?p0        plan:precedes*   ?pCurrent.
                    ?pCurrent  cco:has_output/^cco:specified_by  ?rc.
                    FILTER NOT EXISTS {?pCurrent  plan:precedes  ?p2}.}}
              FILTER NOT EXISTS{?pCurrent   ^plan:precedes*  ?p4.
                ?p4      cco:has_output/^cco:specified_by  ?fNext.}}}}
        GROUP BY ?pCurrent ?fNext}}
    GROUP BY ?pCurrent ?fNext ?rpCount}
  FILTER (?rpCount = ?r5Count)}
FUNCTION{?pNext <- fpsel:ask_to_plan_hole(?fs)
     ?pNext <- fpsel:ask_to_plan_openpocket(?fs)
     ?pNext <- fpsel:ask_to_plan_openslot(?fs)
     ?pNext <- fpsel:ask_to_plan_closedpocket(?fs)
     ?pNext <- fpsel:ask_to_plan_closedslot(?fs)
     ?pNext <- fpsel:ask_to_plan_slab(?fs)
     ?pNext <- fpsel:ask_to_plan_chamfer(?fs)}
```

Fig. 3. Rule to select features according to precedence among them and append the sub occurrence tree planned by the service to generate the complete occurrence tree for the given part

4.2 Plan Processes for Feature

In this study, seven types of standard prismatic features, suitable for CNC machining are considered. Each type of 'feature planning' agent captures this knowledge as a rule, which reads all available process individuals for the compatible process types and assert the required order among them. The available process individuals are read from the process capability knowledge base. The structure of process capability knowledge base (A-Box) and referred ontology is not included for brevity.

The query 'plan-processes-for-feature.rq' (figure 4(a)), recursively selects applicable set of processes from the available processes, respecting the prescribed order of application among them and then tests if the capabilities of any process can satisfy the dimension or tolerance specifications of the feature. At every iteration, the processes, satisfying at least some of the specifications of the feature,

are added to the occurrence tree by creating a new occurrence for such process type. The rule keeps on triggering repetitively, until no process remains in the precedence graph or the feature specification is already satisfied completely.

However, at every iteration, this rule delegates the task of comparing capability and specification for figuring out the suitable process types to a separate matching service, named 'ask_to_select_process'.

4.3 Match Specification Capability

There can be myriad of ways, in which this comparison may be applied, depending on the type of the capability and how they are measured. In this development, most of the capability information are expressed as numerical range. Every instance of process capability is able to satisfy a specific kind of specification, which is linked to the instance of capability by predicate *cco:references*. The rule, given in Figure 4(b), simply tests whether the dimension of the corresponding specification of the feature lies within the maximum and minimum bounds of the capability by applying the FILTER in line 30. The pair of matching capability and specifications are selected by the type of the instance (?dimType) linked to the capability instance (?capa) by *cco:references*. The pattern to select the maximum and minimum bounds are similar and given in line 17-22 and line 24-29 respectively. The pattern follows the information structure of range capability, in which the maximum and minimum bound bearing entity (?maxIBE and ?minIBE) are contained by the corresponding information content entity variables ?maxICE, and ?minICE, distinguished by the maximum measurement ordinal ?maxOrd and ?minOrd, respectively.

The pattern of the query 'match-specification-capability-by-limit' (Figure 4(b)) marks the specifications whose value is contained by the range of a matching capability, as described above. For every satisfied specification, the CONSTRUCT of the rule creates a new instance (?d1) of
`cco:InformationQualityEntity`, which *cco:concretizes* that specification instance (?d). The instance of `cco:InformationQualityEntity` is a real quality, which inheres in the physical feature. As every such real quality instance is linked to the corresponding specification instance, every part produced by following the plan can be associated with the corresponding design specification to tiniest detail.

5 Experiment

This section presents the evaluations conducted to verify the efficacy and performance of this semantic process planning queries, described above, by using several different design specifications as input samples. Some of these sample designs are hand-crafted to test different type of features and associated specifications. These samples are used for testing the planning outcome for individual feature type. In the following sections, the result of planning a hole type feature is presented first. Similar experiments for other types of features, such as slot,

```
PREFIX  resource: <http://www.ohio.edu/services/resources/>

CONSTRUCT{cco:has_output rdf:type  owl:ObjectProperty.
    cco:has_input rdf:type  owl:ObjectProperty.
    plan:precedes rdf:type  owl:ObjectProperty.
    ?f2  rdf:type    design:FormFeature.
    ?pNext1  rdf:type ?pType;
    cco:has_output  ?f2;
    cco:has_input  ?f1.
    ?pCurrent  plan:precedes  ?pNext1.}
WHERE{?p0  rdf:type plan:RootProcess.
    ?p0  rdf:type plan:PlannedProcess.
    ?p0  plan:precedes* ?pCurrent.
    ?pCurrent   rdf:type  ?pt.
    ?pPrevious  rdf:type  ?pt.
    ?pPrevious  plan:hasSucceedingProcess ?pNext.
    ?pNext    rdf:type  ?pType.
    ?pCurrent  cco:has_output    ?f1.
    ?f1      rdf:type          design:IntermediateFormFeature.
    FILTER NOT EXISTS {?pCurrent plan:precedes ?p2}.
    FILTER NOT EXISTS {?f1 cco:concretizes  ?fs}.}
FUNCTION{?f2 <- resource:ask_to_select_process(?f1,?pNext)}
```

(a) plan-processes-for-feature.rq

```
CONSTRUCT{?d1    rdf:type          cco:InformationQualityEntity;
      cco:concretizes    ?d.}
WHERE{?f   rdf:type              design:FeatureSpecification;
    cco:represents    ?r.
 ?fq  rdf:type              design:FeatureQualityMap;
      design:describes_map_with ?f;
    design:describes_map_with ?d.
 ?d    rdf:type       ?dimType;
     cco:inheres_in    ?dm;
    cco:represents    ?rd.
 ?dm  rdf:type        design:MeasurementBearingEntity;
     cco:has_decimal_value   ?dim.
?capa  rdf:type ?capaType;
      cco:references  ?ref.
?ref    rdf:type  ?dimType.
?capa  cco:is_measured_by  ?maxICE.
?maxICE  cco:inheres_in      ?maxIBE;
      cco:is_measured_by  ?maxOrd;
      rdf:type  cco:MeasurementInformationContentEntity.
?maxOrd  rdf:type  cco:MaximumOrdinalMeasurementInformation.
?maxIBE  rdf:type        cco:InformationBearingEntity;
      cco:has_decimal_value  ?max.
?capa  cco:is_measured_by  ?minICE.
?minICE  cco:inheres_in      ?minIBE;
      cco:is_measured_by  ?minOrd;
      rdf:type  cco:MeasurementInformationContentEntity.
?minOrd  rdf:type  cco:MinimumOrdinalMeasurementInformation.
?minIBE  rdf:type        cco:InformationBearingEntity;
      cco:has_decimal_value  ?min.
FILTER (?dim >= ?min && ?dim <= ?max)}
```

(b) match-specification-capability-by-limit.rq

Fig. 4. (a) Rule to generate the sub-occurrence tree for a given feature specification, (b) rule for testing whether the feature has any specification whose value is contained by the range of a matching capability

pocket, and slabs can be found in Sarkar's doctoral dissertation [33]. Then, we present the summary of the planning of a set of three complex parts in section 5.2.

5.1 Planning a hole type feature

The sample hole feature with radius 1.0 mm, depth 2.0 mm, requiring roundness tolerance 0.003, and true position 1.44E-4 mm. The planning for the sample hole feature is conducted by allowing the planner to consider every available processes, realizing `HoleMaking` functions, such as functions of types **HoleStarting**, **HoleMaking**, **HoleImproving**, and **HoleFinishing** and need to be applied in the same order. The sub-occurrence tree for the feature, created by an in-planner plot, is shown in figure 5. The occurrence tree contains every possible route, which can be applied to drill the hole. However, it can be observed that the most of output features of the leaf occurrences are colored red, indicating that those routes fail to satisfy the specifications completely, except only three leaf occurrences: `Reaming_Ir899r1`, `Reaming_I0xgnkm`, and `PrecisionBoring_Ij5f3e1`, having output features colored in green, indicating that a completely satisfied feature is produced. It is apparent from the graph that the planner continued applying the next available process, whenever certain process produced a partially satisfied feature (of type **IntermediateFormFeature**), which are marked in blue.

We analyzed the 'part-4a-plan.rdf' with the analyzer program. The program picks up three valid routes with the following sequence of occurrences, agreeing to the observation from the in-planner graph, shown in Figure 5.

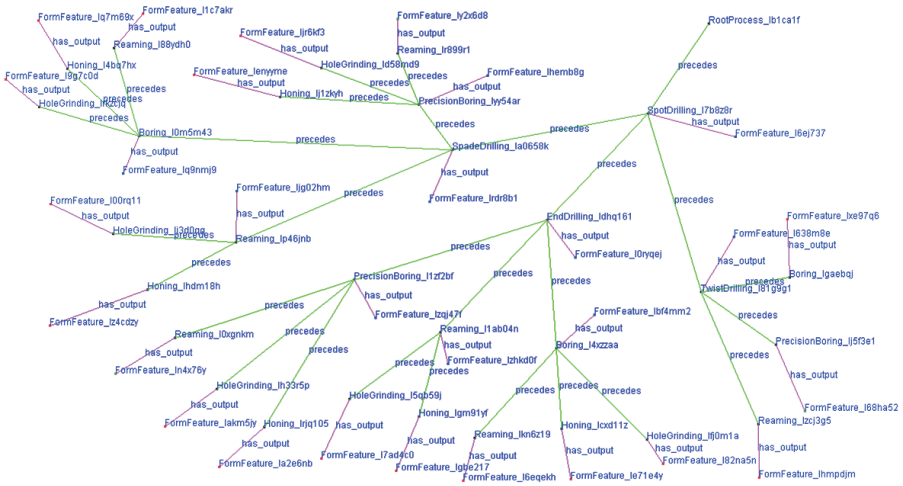

Fig. 5. Sub-occurrence tree of feature 'Test-Hole'.

```
Number of routings planned : 3

Number of occurrences in the routing ending with Reaming_Ir899r1 : 4
SpotDrilling_I7b8z8r@Test-Hole -> SpadeDrilling_Ia0658k@Test-Hole ->
  PrecisionBoring_Iyy54ar@Test-Hole -> Reaming_Ir899r1@Test-Hole

Number of occurrences in the routing ending with Reaming_I0xgnkm : 4
SpotDrilling_I7b8z8r@Test-Hole -> EndDrilling_Idhq161@Test-Hole ->
  PrecisionBoring_I1zf2bf@Test-Hole -> Reaming_I0xgnkm@Test-Hole

Number of occurrences in the routing ending with PrecisionBoring_Ij5f3e1 : 3
SpotDrilling_I7b8z8r@Test-Hole -> TwistDrilling_I81g9g1@Test-Hole ->
  PrecisionBoring_Ij5f3e1@Test-Hole
```

5.2 Practical Design Samples

These standard part designs are originally designed in Siemens NX CAD application and then analyzed by IMPlanner application to generate the corresponding design XML file, which contains the features, associated dimension and tolerances, and machining precedence among the features (given in 6). These design XML files are transformed into RDF graph before the planning rules are triggered.

The planning for the parts are conducted by allowing the queries to consider a set of processes, which can be performed by a combination of CNC machines and tools with variable ranges of capability. These processes maintain a order in their application, which is also stored in the knowledge graph. We want to test whether the planner can find every possible way to produce the part completely. In figure 7, the given occurrence trees (in the same order of the samples in figure 6 are generated by extracting the occurrences and *precedes* relationships among them and plotting in yEd graph viewer. For Netex part, the planner generated total 24960 unique routes to process the part completely. The NIST-CTC-01

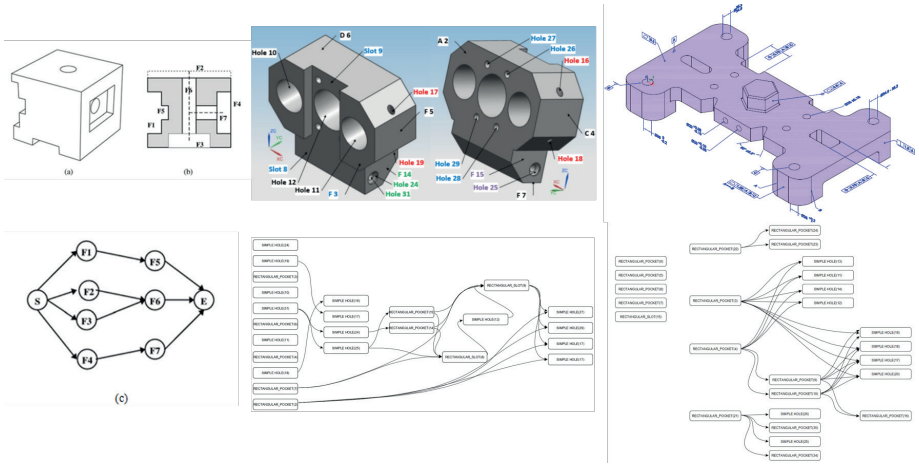

Fig. 6. Sample parts for evaluation

and the Slider part were tested with alternative completely ordered precedences among features in order to avoid longer processing time, however, the alternative processes were allowed. In figure 7, the complete occurrence tree for Netex contains alternatives generated from the partial order among the features as well as the alternative processing routes in the sub-occurrence tree for each feature. Two out of many alternative occurrence tree following various complete order precedence among features are given for Slider part. No such visualization for NIST-CTC-01 part is created because each such complete order occurrence tree itself contains 32768 alternative routes.

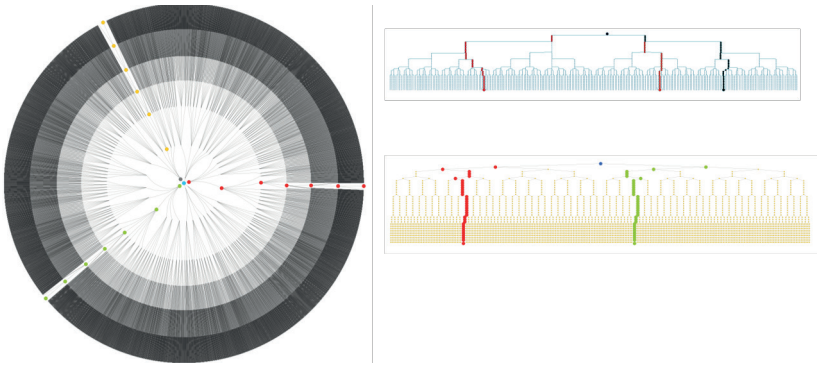

Fig. 7. Occurrence trees produced by the queries for first two sample parts in [**?**]

The colored nodes in the occurrence trees, given in 7, marks different sample routes which are validated by checking the criteria: whether every alternative

route in the occurrence tree is unique, there is at least one process dedicated for each feature in the part, and the features are processed as per the machining precedence among features.

6 Summary and Future Work

The most critical part of the ontology development is the planning ontology, which aims to capture the three dimensional information structure of manufacturing process plan, comprised of aggregation, variety, and time dimension. Except the aggregation dimension, which we do not include in this study, the axioms are heavily motivated by the concepts of process compositions and temporal relationship among occurrences, which are borrowed from PSL with some modifications to adapt to the situation of planning. The output features of the planned processes are also classified based on their conformance to the given specification. Finally, manufacturing process plan is represented as an occurrence tree, which collects every possible route for manufacturing a part completely is represented in a tree structure.

The planning queries are evaluated by a number of sample parts and by constraining it to select from a specific set of alternative processes. The accuracy of these plans is mostly guaranteed by evaluating the criteria, such as whether the plan contains some occurrence for every feature, whether the alternative routes obey the constrains of feature precedence and process precedence, and whether every feature is completely processed or if not, for what reason. Some experiments are conducted with industrial parts, usually containing numerous features, e.g. Netex, Slider, and NIST-01, in order to show the applicability of SIMPlanner in practical cases. However, a complete occurrence tree could not be generated for Slider and NIST-01 in a single run, due to the time-consuming rule in 'part planning agent'. Instead, the experiments are conducted with completely ordered feature precedence, derived from the given partial order among the features, in order to minimize the load on the rule in 3.

The fundamental cause for the increasing amount of execution time for the planner in case of larder parts are due to the fact that the search and update of occurrence at every iteration results in a large derivation tree. A search strategy needs to be implemented in order to guide queries to be executed for only the shortest possible derivation path. As observed in the experiments with a large number of features, the planner consumes an extraordinary amount of time. In a distributed manufacturing environment, this problem will be exacerbated by the sheer volume of alternative resources (machines, tools, and suppliers). A number of space-search algorithms, such as A*, may be applied with a suitable heuristic to avoid expanding some of the alternative routes further. These type of bounding algorithms need to be embedded in the queries of part planning and feature planning agents.

In order to extend the prototype, presented in this study, for handling process planning for other domains of manufacturing, such as assembly, metal stamping, forging, injection molding, and 3D printing, the domain level ontology needs to

be furnished with taxonomies of concepts from these domains. For this purpose, a detailed investigation needs to be conducted for each of these domains to gather the list of processes, functions, and capabilities of machines and tools, used in these domains. Furthermore, various domains level planning knowledge, precedence among processes, material conditions, and general best practices need to be encoded in the rules of the agents. Some of the planning related concepts in other domain may even require certain adjustments in the definitions of upper level concepts. Such an endeavor definitely coincides with the current work of Industrial Ontology Foundry in developing a global ontology for manufacturing. In the future, the proposed model of upper level manufacturing ontology is expected to converge.

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A Novel Framework for the Shop-floor Scheduling Nervousness.

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Abstract. In this contribution, a novel framework for the Shop-floor Scheduling Nervousness (SN) is presented. The SN is defined as an evolving state associated to an on-going schedule domain. The approach is suitable to be instantiated within industry 4.0 manufacturing environments.

Keywords: Nervousness, Online Scheduling, Industry 4.0.

1 Introduction

Traditionally, the production scheduling problem has been addressed by means of (i) predictive approaches, (ii) robust proactive approaches, and (iii) predictive-reactive approaches. In practice and due to their intrinsic and complex dynamic nature, industrial plants constantly face unexpected events and changes on the expected performance (Novas & Henning, 2010). Thus, scheduling at real contexts needs to be addressed by means of online approaches, in order to continuously revise the agenda.

Nevertheless, even when immediate rescheduling actions are performed each time a disruption or deviation occurs in order to get a new feasible/good quality solution, this adaptation-to-change response mechanism might not be well accepted on the shop-floor. That is because repeated changes could lead to a continuous rearrange of predefined plans on the shop floor, and through all the plans linked, even up to the supply chain level. This undesired behavior is known in practice as *nervousness*. Since changes occur on plans at different areas, nervousness also exists at different levels. Nervousness happens in MRP systems and it has been studied for many years (Belmokhtar et al., 2010). This kind of nervousness has to do, mainly, with changes on the production orders plan and has been identified in the literature as *scheduling nervousness* (or its counterpart *scheduling stability*). Nervousness also occurs at the control systems level, where it has received increasing attention (Hadeli et al., 2006).

Yet, further interpretation and specification of the nervousness happening at the shop floor level, where a short-term on-going schedule drives the production agenda, is needed. The *shop-floor scheduling nervousness* (SN) exists because of the intrinsic connections among the planning and shop domain entities. Thus, the efficient control of the SN is a key issue to be handled in order to have efficient scheduling support systems. Here, advances on a novel framework to characterize the SN are presented.

2 A Shop-Floor Scheduling Nervousness Framework

The presented framework is aimed at providing a conceptual ground over which approaches intended to identify and manage SN can be developed. In this section, some insights of the features that characterize the proposed shop-floor nervousness are identified (the complete framework is not described here because of lack of space).

The SN Scope. A definition of shop-floor scheduling nervousness is provided, with the aim of distinguishing the main aspects that characterize it. The SN is identified as a *state* of the shop schedule, which represents a latent state of inefficient behaviors, that exists at every time point along the scheduling horizon, while the shop is executing production orders, which results from (i) what has already happened in the recent past, during the already executed portion of the on-going schedule, (ii) what has occurred in past executed agendas and represented by historical data, and (iii) what is not happened yet, but either it is planned and/or can be expected based on that historical data. From the SN management it can be expected to: (i) Kip track of the past changes on the agenda. Allowing to optimize performance measures, like the cost-related ones, at any reactive activity, and at the same time, to know the deterioration of the agenda along the scheduling horizon caused by disruptions. (ii) Determines the more suitable reactive/adaptive actions to implement. For instance, some change over a given schedule entity might be forbidden if a certain nervousness threshold is overpassed. (iii) Known a nervousness trend of the global agenda, as well as for each individual domain entity (resources and jobs, mainly).

Relations among Rescheduling, Stability & Nervousness. The *reactive scheduling* or rescheduling activity is intended to update and adapt an on-going agenda. It can be carried out periodically, triggered by a disruptive event, or by a hybrid policy. A reactive scheduling task occurs at a certain time point within the schedule horizon and pursues the rearrangement of the agenda trying not to degrade the schedule performance. *Stability*, then, is a natural objective of a rescheduling task. Considering stability leads to a reactive action that tries to change as less as possible the properties of the on-going schedule. This means that the values the temporal variables have, the assignments of operations to resources, and all related planned decisions, will be maintained as much as possible.

At this point, it is possible to differentiate between nervousness and stability. While *nervousness* represents a state of the shop, the stability is an objective to reach each time a rescheduling action takes place. Nevertheless, nervousness and stability are highly related. A shop will increase its nervousness when the changes through time (as results of rescheduling tasks) have a cumulative negative impact on stability measures. A highly nervous shop arises as a consequence of the system inability to efficiently manage its stability through time.

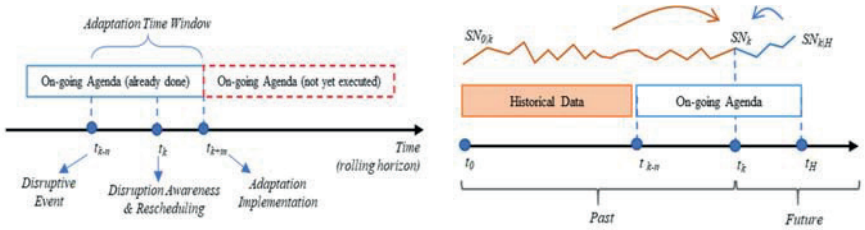
The SN not only is related with the stability of the agenda, but to its performance too. How potential modifications on schedule entities can impact on an efficiency performance measure is also associated with the SN concept. The more related the domain variables are, the higher SN is. Historical statistical analysis can show in-

sights about the correlation among different entities/variables, which in turn can be helpful to predict a probable behavior when changes occur on those variables.

Time-related features. Having a SN characterization requires an explicit domain specification. Among other relevant domain issues, diverse types of time-points associated with different schedule knowledge are identified. Fig. 1 (a) shows some of these time points, which correct management is essential in order to effectively apply an adaptation to an on-going agenda.

As it was already stated, the SN strongly depends on time: the more unstable a manufacturing shop was in the past, the more uncertainty about its future it has, and therefore, the more nervous it is in the present.

Let's say there is an on-progress schedule at time t_k, as it is shown in Fig. 1 (b). The schedule has started its execution n periods of time before t_k and the activities will be finished at t_H, as planned. The shop nervousness value at t_k, SN_k, is influenced by historical data, from t_0 to t_{k-n}, the already executed portion of the on-going schedule data, from time point t_{k-n} to t_k, as well as for the SN predicted values from t_k to t_H.



(a) (b)

Fig. 1. (a) The proximity among the depicted time-points will depend on the automation and complexity level of the shop-floor and production agenda. (b) Schematic representation of the past data and forecasted data making impact in the current SN at t_k.

Part of the novelty of this proposed framework is the consideration of the future into the online schedule system. The past behavior of schedule entities can be analyzed and, when it is feasible, future behavior can be predicted by statistics or AI based methods. Thus, not only past events and current status impacts on SN state, but the predicted future values too.

3 A conceptual model for SN in practice

As it was stated, the SN is related with an on-going agenda, their domain entities, the historical and recent past data, and the forecasted data, considering uncertainty when it is suitable. Here and because of lack of space, just an illustrative insight of a developed conceptual model is described.

A production schedule can be acknowledged as a set of planned events that are linked to domain entities, such as the production tasks. These tasks have temporal properties, creating an agenda for the jobs and their required operations. Therefore,

shop schedule properties such as its performance, and domain entities attributes like a tardiness associated with a job, can be identified and measured.

There is also historical data associated with some of the entities, such as jobs and resources. This data can be used to know the behavior that characterizes them. From this information, features such as a probability of failure of a machine, probability of tardiness completion of a job, among another relevant knowledge, can be estimated. Likewise, the nervousness associated with an entity can be estimated.

The linkage of the shop schedule and other related plans is a fundamental part of a nervousness estimation, since it has to do with the potential impact of a given plan over other ones. This can be tackled, for instance, as part of correlation analysis.

The unexpected disruptive events have also to be incorporated as part of a SN framework. There is a set of unplanned events that cannot be predicted, but there are other many events over which a prediction can be done, in terms of their probability of occurrence. Disruptions caused by a broken machine, a new urgent job, a discontinuation of a raw material supply, among others, sometimes may have a given behavior based on a given probability of occurrence. Thus, that behavior can be estimated.

Knowing a global level of SN will allow to take more effective and efficient decisions each time the agenda needs to be adapted or changed. For instance, a shop with a low level of nervousness can take more changes to the ongoing agenda than one with a higher level of nervousness. In a high nervous system, there is small room for alterations to what is already planned. This means that not necessarily each rescheduling action requires to minimize as much as possible changes: The level of enabled changes will depend on the level of nervousness the system has at that time point.

4 Conclusions

In this work, a novel framework for the Shop-floor Scheduling Nervousness is presented. It is intended to define the SN as an evolving state associated to an on-going schedule domain. In this conceptual-based framework different features characterizing the SN are identified. The contribution describes a novel schedule revision approach, that considers not only past and current data, but future estimated data, too. Based on this framework, diverse approaches, models and metrics can be developed and tested within diverse manufacturing environments.

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Modelo de Maturidade PLM (Product Lifecycle Management) com Conceitos da Indústria 4.0 – Avaliação com base no método AHP

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Abstract. Com fábricas e produtos inteligentes, mudanças ocorrerão na maneira como os produtos serão fabricados, impactando em vários setores do mercado. O PLM mantém a promessa de integrar e disponibilizar todas as informações produzidas durante as fases do ciclo de vida de um produto. A Indústria 4.0 (I4.0) propõe uma gestão eficiente de dados, disponibilidade, confiabilidade e responsividade, permitindo que decisões sejam tomadas em tempo real. Com base no portfólio obtido da revisão da literatura, uma comparação cruzada entre a I4.0 e o PLM foi conduzida sob a ótica das dimensões de maturidade e principais perspectivas de cada área, no sentido de identificar lacunas e oportunidades de pesquisa. O trabalho foi desenvolvido com o objetivo de avaliar a maturidade de uma organização do ramo de eletrodomésticos no contexto do PLM relacionados com atributos da indústria 4.0. Para tal, foi elaborado um modelo de maturidade, a partir da relação entre os principais atributos da I4.0 e as fases do ciclo de vida do produto. Com base neste modelo o diagnóstico do nível de maturidade foi realizado através do método AHP avaliando a importância relativa dos critérios que caracterizam atributos da I4.0 e dimensões do PLM. Os resultados obtidos indicam que a empresa se encontra em Nível 3 de maturidade.

Keywords: PLM, Indústria 4.0, Modelo de Maturidade, AHP.

1 Introdução

A Indústria 4.0 é um conjunto de tecnologias que proporcionam numerosos benefícios ao setor industrial. A também chamada de 4ª Revolução Industrial contribui para personalização das empresas no mercado, a gestão do conhecimento organizacional e a qualificação dos colaboradores nesta nova etapa dos processos produtivos (SCHWAB, 2016).

A Gestão do Ciclo de vida de Produto, também conhecida como PLM (*Product Lifecycle Management*), é um conceito de gestão constituída de dados relacionados aos produtos e processos, ao longo do seu ciclo de vida (SAAKSVOURI; IMMONEN, 2008, p.15; ZANCUL, 2009, p.1). Está se tornando uma parte fundamental dentro das empresas para gerar valor sustentável e concorrência, no qual os consumidores estão interessados nos impactos ambientais das mercadorias consumidas (GUELERE FILHO *et al*., 2009, p.2).

Com a integração da Indústria 4.0 e o PLM em todas as etapas de fabricação é possível obter um melhor gerenciamento do mesmo, com respostas mais rápidas e fáceis, permitindo que o aproveitamento dos dados impulsione o sistema produtivo, pois cada setor possui um desafio e uma necessidade diferente. Diante desse cenário, parâmetros de classificação quanto a maturidade das organizações para o emprego de produtos relacionados as exigências da Indústria 4.0 podem ser usados como alternativa para monitorar e garantir eficiência no emprego de projetos que exigem cada vez mais flexibilidade e performance.

Cristofari Junior *et al.* (2010), descreve a grade de maturidade como "estruturas que apresentam uma descrição qualitativa das áreas estratégicas do processo". Para os autores, o melhor modelo de maturidade a ser aplicado é aquele que aplica a grade de maturidade juntamente com modelos de capacidade. O resultado desse modelo de maturidade é o emprego de um questionário sobre as melhores práticas do processo avaliado, no qual o colaborador avaliou as práticas de acordo com uma escala variante de 0 a 4. O resultado dessa avaliação permite definir o grau de maturidade do segmento.

O presente trabalho contribui para a formalização de um modelo diagnóstico de maturidade no segmento da indústria de eletrodomésticos, de forma a suportar uma avaliação diagnóstica e decisional para o estabelecimento de um plano de diretrizes e melhorias.

A Figura 1 representa o fluxograma da pesquisa, as quais foram separadas em etapas. Para o desenvolvimento deste trabalho foi utilizada, em uma primeira etapa, uma revisão da literatura para melhor entendimento dos conceitos relacionados aos modelos de maturidade caracterizando os atributos da Indústria 4.0 e o PLM. Na segunda etapa foi elaborada uma matriz relacional com o intuito de identificar a intensidade da relação entre os atributos da I4.0 e o PLM, caracterizando-os em nula, fraca, média ou forte relação. Logo em seguida, com os atributos selecionados, foram realizadas fichas de avaliação, as quais serviram como base para elaboração da quarta etapa, que caracterizou a estruturação do método AHP e a aplicação do mesmo tendo como resultado o diagnóstico do nível de maturidade atual da empresa.

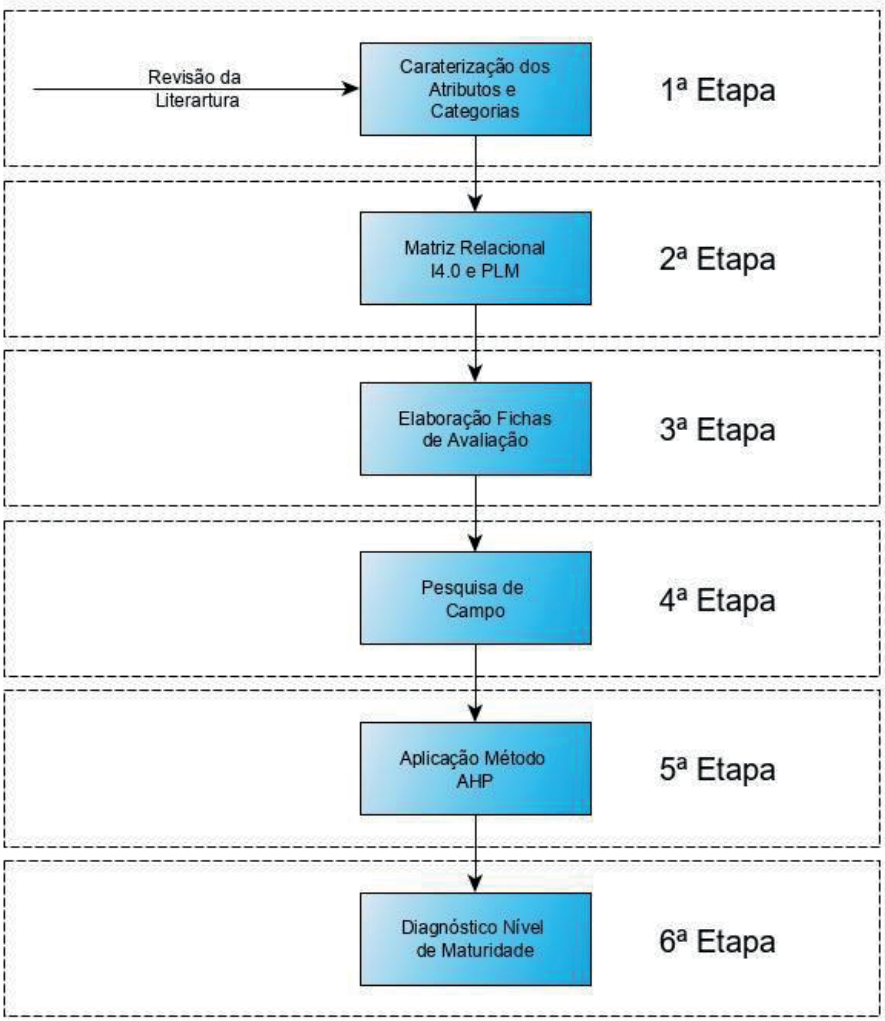

Fig. 1. Fluxograma de Pesquisa

O presente artigo é estruturado da seguinte forma. Na Seção 2, os conceitos básicos da Indústria 4.0, PLM e seus respectivos modelos de maturidade são apresentados. Na Seção 3 é aplicado o método da matriz relacional para a seleção dos atributos a serem utilizados na avaliação. Na Seção 4 é feita a análise diagnóstica através do método AHP sendo os resultados discutidos na Seção 5. As considerações finais são apresentadas na Seção 6, destacando algumas limitações deste artigo e sugestões para futuras pesquisas sobre o assunto.

2 Base conceitual

2.1 Indústria 4.0 Modelos de Maturidade

A respeito de seu surgimento, Hahn Filho (2016) afirma que o conceito de Indústria 4.0 foi exposto para o público geral em 2011, na feira de Hannover, propondo uma ruptura de paradigma na maneira como as fábricas operam. Os pilares que conceituam a indústria 4.0 já são utilizados na manufatura, porém sua integração transformará a produção, consolidando fluxos integrados, otimizados e automatizados e mudando as tradicionais relações entre fabricantes, fornecedores e clientes, bem como humanos e máquinas (RÜßMANN *et al*, 2015). De acordo com os autores, são oito os principais pilares de sustentação: a) *Big Data and Data analysis;* b) *Autonomous robots;* c) *Simulation*; d) *Internet of things*; e) *Cyber-physical systems* (CPS); f) *Cyber security;* g) *Cloud;* h) *Additive manufacturing;*

Um modelo de maturidade descreve em um espaço de tempo as capacidades específicas dentro de uma organização (HYNDS *et al*, 2014). A maturidade de uma empresa pode ser entendida como uma medida de sua excelência dentro da organização. Os modelos de maturidade descritos são alguns dos disponíveis na literatura referente a Indústria 4.0.

O Impuls-VDMA é uma ferramenta de auto avaliação criada pela Associação Alemã de Fabricação de Máquinas e Instalações Industriais (VDMA) juntamente com a fundação Impuls, que é aplicada por empresas para o conhecimento do seu nível de preparação e condições para a transformação promovida pela Indústria 4.0 (SANTOS; MARTINHO, 2018).

O I4.0 *Maturity Model*, modelo proposto por Schumacher *et al*. (2016) apresenta oito dimensões envolvendo diferentes perspectivas. 1º Dimensão – *Strategy: Implementation I40 roadmap; Available Resources for realization; Adaption of business models.* 2ª Dimensão – *Leadership: Willingness of leaders; Management competences and methods; Existence of Central coordination for I40*. 3ª Dimensão – *Customer: Utilization of customer data; Digitalization of sales/services; Customer's Digital media competence*. 4ª Dimensão – *Products: Individualization of products; Digitalization of Products; Product Information into other systems*. 5ª Dimensão – *Operations: Decentralization of processes; Modeling and simulation; Interdisciplinary; Interdepartmental*. 6ª Dimensão – *Culture: Knowledge sharing; Open-innovation and cross company collaboration; Value of ICT in company*. 7ª Dimensão – *Governance: Labour regulations for I40; Suitability of employees to new technology; Autonomy of Employees*. 8ª Dimensão – *Technology: Existence of modern ICT; Utilization of mobile devices; Utilization of machine-to-machine communication*.

O modelo proposto por Leyh *et al*. (2017), chamado de *System Integration Maturity Model Industry* 4.0 (SIMMI), é composto por quatro dimensões: *vertical Integration, horizontal integration, digital products development* e *cross technology*. A dimensão *vertical integration* diz respeito aos componentes dos níveis mais baixos da organização, em que objetos físicos, como produtos e máquinas, precisam trocar informações entre esse nível e entre níveis superiores. *Horizontal integration* trata da cadeia de valores, na qual é necessário um fluxo automatizado e integrado de informações no nível

horizontal da cadeia e fora dele, permitindo interoperabilidade entre os envolvidos na cadeia de suprimentos. A dimensão *digital products development* envolve a representação digital, na qual pelo menos um sistema deve estar integrado a uma etapa do processo. A dimensão *cross technology* é fundamentada na avaliação de quais tecnologias são adotadas nos diferentes campos da indústria 4.0

Schuh *et al*. (2017) propõem o modelo Acatech Maturity Index, composto de quatro dimensões: *resources, information systems, culture e organizational structure*. A dimensão *resources* refere-se à recursos, contemplando a força de trabalho da companhia (recurso humano), máquinas e equipamentos, ferramentas, materiais e o produto final. *Information systems* preparam, processam, armazenam e transferem dados e informações. A dimensão *culture* parte da premissa que as organizações não poderão alcançar seus objetivos e o desejo de agilidade se simplesmente introduzirem tecnologias digitais sem abordar a cultura corporativa. *Organization structure* refere-se no modelo proposto à organização interna da companhia (estrutura e processos operacionais) e sua posição quanto a cadeia de valores, estabelecendo regras que organizam a colaboração interna e externa (SCHUH *et al*, 2017).

2.2 Product Lifecycle Management e Modelos de Maturidade

Para Amann (2002) a concepção do PLM é uma abordagem estratégica para criação, gerenciamento e uso eficaz do capital intelectual corporativo, desde a concepção inicial de um produto até sua aposentadoria. Li *et al*. (2015) ponderam uma ideia básica desses processos, começando pela fase de design, na qual uma ideia é concebida em uma descrição detalhada, seguindo para a fase de produção, onde o produto final é elaborado e na fase logística é armazenado e transportado para o cliente, que pode fazer o uso de seu produto enquanto o fabricante provê serviços fundamentais. Se o produto vier a apresentar defeito, a manutenção entra em questão e caso o produto não possa mais ser usado, chega ao fim de sua vida com a reciclagem ou descarte. As fases que envolvem esses processos dividem-se basicamente em três períodos característicos: *beginning of life* (BOL), *middle of life* (MOL) e *end of life* (EOL).

De acordo com Li *et al*, 2015 os principais atributos inseridos no início de vida do produto (BOL) são: *Customer's Demands, Maintenance and failure information, Cooperative corporation information, Design specifications: Bill of material, Production Information*. Já na fase MOL são: *User manual, Production Information, Maintenance supporting information, Product status information, Usage environment information, Maintenance plan*. No EOLtemos: *Maintenance history information, Product status information, Usage environment information, Recycling part information, EOL product status information, Dismantling information.*

3 Análise relacional da I4.0 e PLM

Para a priorização dos itens com maior influência no ciclo de vida do produto em relação aos pilares da Indústria 4.0, foi aplicado uma matriz relacional, representado em parte na Figura 2, selecionando os atributos dos modelos de maturidade com cada fase do modelo de PLM. Os modelos de Maturidade da Industria 4.0 estudados foram: Impuls – VDMA, I4.0 Maturity Model, Simmi 4.0 e Index (Acatch) e os modelos de maturidade do PLM foram: Stark, Kärkkäinem, Saaksvuori, Zhang e Terzi. Na aplicação da ferramenta, foi comparado cada atributo da I4.0 com os atributos de todas as fases do PLM, a qual estava sendo avaliada e os autores efetuaram a classificação com uma nota que variou entre 0 (nula), 1 (fraca relação), 3 (média relação) e 9 (forte relação).

MM I4.0			MM PLM		
			BOL		
Maturity Models	Dimensions	Attributes	Customers Demands	Cooperative Corporation Information	Production Information
IMPULS	Strategy and Organization	Strategy	0	1	0
IMPULS	Strategy and Organization	Investment	3	0	0
IMPULS	Strategy and Organization	Inovatsion Management	0	0	0
IMPULS	Smart Factory	Digital Modeling	1	0	3
IMPULS	Smart Factory	Equipment infrastructure	1	0	0
IMPULS	Smart Factory	Data Utilization	9	9	9
IMPULS	Smart Factory	IT Systems	1	1	0

MM I4.0			MM PLM			
			MOL			
Maturity Models	Dimensions	Attributes	User Manual	Product Status Information	Usage Environment Information	Maintenance Plan
IMPULS	Strategy and Organization	Strategy	0	1	1	1
IMPULS	Strategy and Organization	Investment	0	0	0	0
IMPULS	Strategy and Organization	Inovatsion Management	0	0	0	1
IMPULS	Smart Factory	Digital Modeling	0	0	0	1
IMPULS	Smart Factory	Equipment infrastructure	0	0	0	3
IMPULS	Smart Factory	Data Utilization	1	9	9	3
IMPULS	Smart Factory	IT Systems	0	0	0	0
IMPULS	Smart Products	Information, communication and technology integrated to product features	1	3	3	1
IMPULS	Smart Products	Data analysis	0	9	9	9
IMPULS	Data-Driven Services	Data sharing	1	1	1	9
IMPULS	Data-Driven Services	Result sharing	0	0	0	1

MM I4.0			MM PLM			
			EOL			
Maturity Models	Dimensions	Attributes	Maintenance History Information	Usage Environment Information	EOL product status information	Dismantling Information
IMPULS	Strategy and Organization	Strategy	1	1	0	0
IMPULS	Strategy and Organization	Investment	0	0	0	0
IMPULS	Strategy and Organization	Inovatsion Management	0	0	0	0
IMPULS	Smart Factory	Digital Modeling	0	0	0	0
IMPULS	Smart Factory	Equipment infrastructure	1	0	0	0
IMPULS	Smart Factory	Data Utilization	9	9	9	9
IMPULS	Smart Factory	IT Systems	0	0	0	0
IMPULS	Smart Products	Information, communication and technology integrated to product features	1	3	1	0

Fig. 2. Recorte da Matriz QFD.

Como resultado da análise relacional da I4.0 e PLM através da ferramenta matriz relacional, foram selecionados todos os atributos com nota 9, ou seja, caracterizado forte relação e entre os atributos escolhidos foram selecionados 4 para cada fase do PLM, os quais possuíam um panorama ligado a análise de dados relacionado ao cliente e informações de manutenção do produto.

Para a realização da pesquisa foi apresentado aos colaboradores fichas de avaliação (Figura 3) descrevendo os quatro níveis de maturidade, com informações sobre a fase

do PLM, descrição do atributo, proposta, ou seja, como o atributo será avaliado na dimensão proposta, indicadores de avaliação, o resultado e a diretriz a ser tomada para atingir próximo nível.

Fase do PLM	BOL
Atributo	Customers Data
Atributo Relacionado	Demanda do Cliente (Customers Demand)
Nível de Maturidade	Nível 1
Descrição do Atributo	São esperados dados do cliente relacionados à necessidade da função do produto, configurações, embalagens, custo e outras expectativas. A empresa utilizará esses dados (informações) para o processo de desenvolvimento de produto.
Proposta	Verificar como esses dados são informados pelo cliente e como a empresa irá utiliza-los.
Indicadores de Avaliação	a) Disponibilidade dos dados b) Clareza dos dados c) Compartilhamento dos dados d) Divulgação dos dados
Resultado	Não há o compartilhamento de dados dos clientes e a empresa realiza o processo de desenvolvimento de produto sem essas informações.
Diretriz	Promover um melhor compartilhamento das informações (parcial).
Alternativas para sobrepor atributo selecionado	Sugerem algumas propostas para que os dados (níveis de informações) tenham evoluções

Fase do PLM	Fase do PLM em que se encontra o atributo: BOL / MOL / EOL
Descrição do Atributo	Descrição do atributo considerando o quadrante a que pertence
Proposta	Como o atributo será avaliado na dimensão proposta
Indicadores de Avaliação	Que pontos e critérios serão avaliados na organização
Resultado	Descrição da informação do atributo relacionado ao nível de maturidade
Diretriz	Recomendação de melhores práticas
Alternativas para sobrepor atributo selecionado	Propostas de alternativas para sobrepor o atributo

Fig. 3. Exemplo ficha de avaliação.

Entrando na etapa de pesquisa de campo, esta foi aplicada para 10 colaboradores envolvendo diversos departamentos da empresa com cargos de gestão como: Diretores, engenheiros de manufatura, logística e qualidade. O questionário foi desenvolvido em duas fases, sendo a primeira com o objetivo de perceber o grau de relevância entre os atributos da Indústria 4.0 de cada fase do PLM. Para a realização desta fase foi perguntado ao colaborador qual atributo correlacionado ele identificava com maior relevância dentre as fases do PLM os dados obtidos desta fase estão descritos na Figura 4.

BOL		MOL		EOL	
Atributo Relacionado	QTD	Atributo Relacionado	QTD	Atributo Relacionado	QTD
Data Analysis	3	Remote Monitoing	3	Data Utilization and Analysis	3
Data Information Sharnig	2	Custumers Focus	2	Data Analysis	2
Custumers Data	2	Data Analysis (Product Status Inf.)	2	Remote Monitoing	2
Data Utilization	3	Data Analysis (Usage Environment)	3	Custumer Data Integration	3

Fig. 4. Dados obtidos primeira etapa da pesquisa.

As fichas de avaliação serviram de suporte para responder o quadro de avaliação, o qual está representado de maneira genérica na Figura 5.

Fase do ciclo de vida do produto (BOL/MOL/EOL)												
Atributo 01					Atributo 02					Atributo 03				
Atributo Relacionado X	Nível				Atributo Relacionado Y	Nível				Atributo Relacionado Z	Nível			
	1	2	3	4		1	2	3	4		1	2	3	4

Fig. 5. Modelo quadro de avaliação.

Como resultado da segunda fase da pesquisa o colaborador leu as fichas referentes ao atributo correlacionado e assinalou no quadro de avaliação qual nível a empresa se encontra de acordo com sua percepção. A Figura 6 representa as respostas da pesquisa analisando os atributos com fortes relações dos modelos de maturidade da Industria 4.0 com a fase inicial do PLM.

	BOL			
	Customers Demands	Customers Demands	Cooperative Corporation Information	Production Information
Função	Customers Data	Data Analysis	Data Information Sharing	Data Utilization
Vice Presidente - Produto	4	4	3	4
Eng. Manufatura	3	2	2	2
Analista jr (compras)	3	3	4	4
Analista (Manutenção)	3	3	4	3
Gerente de Logística	3	2	4	2
Programador Produção	3	3	3	3
Eng. Qualidade	3	3	3	4
Eng. Jr. De Produto	3	2	3	3
Eng. Qualidade	4	3	3	4
Analista (Plan. Produção)	3	2	2	3

Fig. 6. Resultados segunda etapa da pesquisa fase BOL.

Já a Figura 7 descreve as respostas referentes ao meio do ciclo de vida do produto.

	MOL			
	User Manual	Product Status Information	Maintenance Plan	Usage Environment Information
Função	Customer Focus	Data Analysis	Remote Monitoring	Data Analysis
Vice Presidente - Produto	4	3	1	4
Eng. Manufatura	2	1	4	2
Analista jr (compras)	2	3	4	4
Analista (Manutenção)	4	3	3	3
Gerente de Logística	3	3	4	3
Programador Produção	3	4	4	3
Eng. Qualidade	4	3	2	4
Eng. Jr. De Produto	2	3	2	2
Eng. Qualidade	3	3	3	4
Analista (Plan. Produção)	2	1	3	3

Fig. 7. Resultados segunda etapa da pesquisa fase MOL.

E a Figura 8 traz os resultados obtidos da fase final do ciclo de vida do produto.

	EOL			
	Maintenance History Information	Usage Environment Information	EOL product status information	Dismantling Information
Função	Remote Monitoring	Data Analysis	Data Utilization and Analysis	Customer Data Integration
Vice Presidente - Produto	3	4	4	1
Eng. Manufatura	3	2	2	1
Analista jr (compras)	3	4	4	4
Analista (Manutenção)	4	3	4	3
Gerente de Logística	4	2	3	2
Programador Produção	3	3	3	2
Eng. Qualidade	3	4	2	2
Eng. Jr. De Produto	4	4	4	3
Eng. Qualidade	3	3	4	2
Analista (Plan. Produção)	2	3	2	1

Fig. 8. Resultados segunda etapa da pesquisa fase EOL.

Os dados obtidos através da pesquisa com os colaboradores foram compilados em uma tabela e efetuado o cálculo da média simples, conforme a Figura 9.

	Atributos (Atributos Relacionados)	Média	Atributos (Atributos Relacionados)	Média	Atributos (Atributos Relacionados)	Média	Atributos (Atributos Relacionados)	Média
BOL	*Customers Demands (Customers Data)*	3,2	*Customers Demands (Data Analysis)*	2,7	*Cooperative Corporation Information (Data Information Sharing)*	3,1	*Production Information (Data Information*	3,2
MOL	*User Manual (Customer Focus)*	2,9	*Product Status Information (Data Analysis)*	2,7	*Maintenance Plan (Remote Monitoring)*	3	*Usage Environment Information (Data Analysis)*	3,2
EOL	*Maintenance History Information (Remote Monitoring)*	3,2	*Usage Environment Information (Data Analysis)*	3,2	*EOL Product Status Information (Data Utilization and Analysis*	3,2	*Dismantling Information (Customer Data Integration)*	2,1

Fig. 9. Média das respostas dos colaboradores.

4 Aplicação Método AHP

O AHP é um método desenvolvido para ajudar empresas e pessoas a tomar decisões mais complexas, embasando a escolha em múltiplos critérios, podendo um parâmetro ter maior peso em relação ao outro. O objetivo da aplicação do método AHP é determinar a importância que os atributos correlacionados exercem nas alternativas, ou seja, nos níveis de maturidade. A abordagem avaliativa inspira-se no trabalho (Cestari *et al,* 2017, p. 1-37) o qual utiliza o AHP para uma avaliação de diagnóstico relacionado a comparação dos atributos para a par. Através desta avaliação também será possível especificar a relevância dos atributos correlacionados dentro de cada fase do PLM. Foi elaborado uma estrutura mais simplificada do Método AHP, conforme a Figura 10.

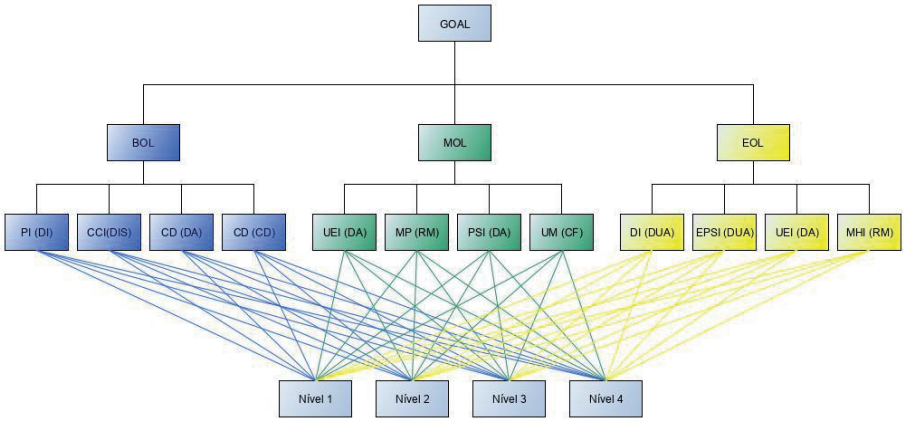

Fig. 10. Estrutura hierárquica do método AHP.

A estrutura do AHP apresentada na Figura 10, foi desenvolvida com o objetivo de proporcionar uma avaliação do PLM com conceitos da indústria 4.0, utilizando como critérios do método AHP as 3 fases do PLM (BOL, MOL e EOL) e como subcritérios os atributos associados com forte relação oriundos da matriz relacional, sendo estes: Para BOL *Production Information (Data Information) "PI(DI)"*; *Cooperative Corporation Information (Data Information Sharing) "CCI(DIS)"; Customers Demands (Data Analysis)"CD(DA)* e *Customers Demands (Customers Data) "CD(DA)"*. Para o MOL *Usage Environment Information (Data Analysis) "UEI(DA)"; Maintenance Plan (Remote Monitoring) "MP(RM)"; Product Status Information (Data Analysis) "PSI(DA)"* e *User Manual (Customer Focus) "UM(CF)"* e para o EOL *Dismantling Information (Customer Data Integration) "DI(DUA)"; EOL Product Status Information (Data Utilization and Analysis "EPSI(DUA)"; Usage Environment Information (Data Analysis) "UEI(DA)"* e *Maintenance History Information (Remote Monitoring) "MHI(RM)"*. Como alternativa estão os níveis de maturidade, os quais indicam o posicionamento da organização onde o diagnóstico definirá o nível de maturidade.

A atribuição de valores para a conversão dos critérios foi definida de acordo com as médias das respostas dos colaboradores. A primeira fase teve como objetivo determinar quanto um critério é mais importante que o outro dentro de cada fase do PLM, sendo este apontado como o de maior peso na decisão.

O modelo diagnóstico propõe uma escala de 4 níveis de maturidade e a escala AHP é composta de pesos de 1 a 9. Para o cálculo da matriz de conversão, foi dividido o grau mais alto da escala AHP pelo número de níveis do modelo diagnóstico. Os resultados obtidos foram arredondados e seus resultados encontram-se na Table 1.

O software que ofereceu suporte para a resolução dos cálculos do método foi o SuperDecisions.

Alternativa Fichas de Avaliação	Escala AHP
Nível 1	2
Nível 2	5
Nível 3	7
Nível 4	9

Table 1. Matriz de conversão.

No início do ciclo do de vida do produto (BOL) os atributos que apresentaram maior relevância foram *Customers Demands* (*Data Analysis*) e *Production Information* (*Data Information*), ambos com resultado de 37,5%, conforme apresentado na Figura 11.

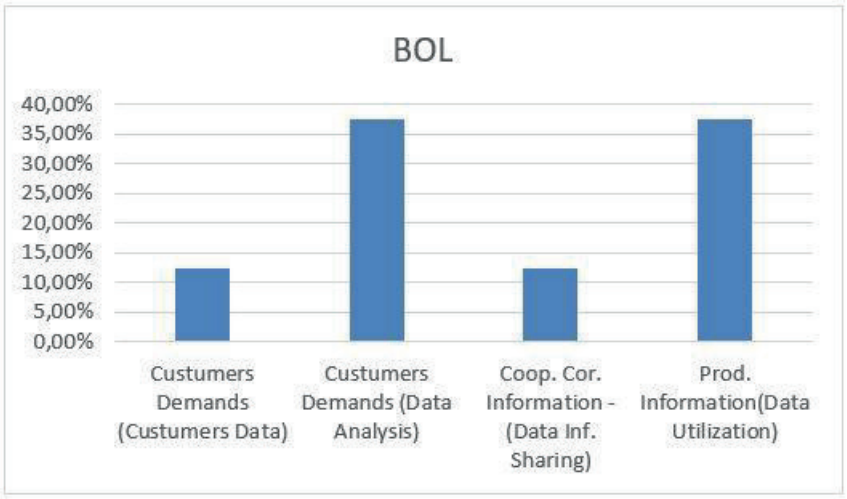

Fig. 11. Comparação gráfica atributos BOL.

Para a *Middle of Life*, a qual diz respeito a fase em que o produto é estabelecido, dentro das respostas coletadas o atributo *Maintenance Plan* (*Remote Monitoring*) tem maior relevância nessa fase, atingindo 54,16% conforme apresentado na Figura 12.

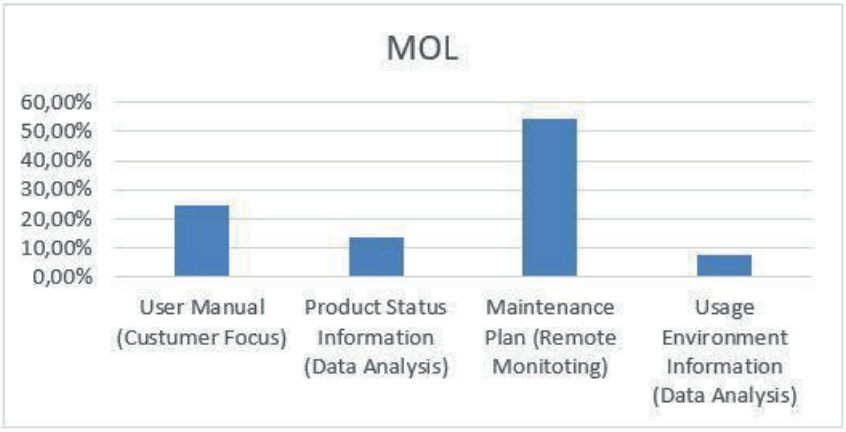

Fig. 12. Comparação gráfica atributos MOL.

A última fase do ciclo de vida (EOL) o atributo *Maintenance History Information* (*Remote Monitoring*) apresentou 44,8% de relevância, de acordo com a Figura 13.

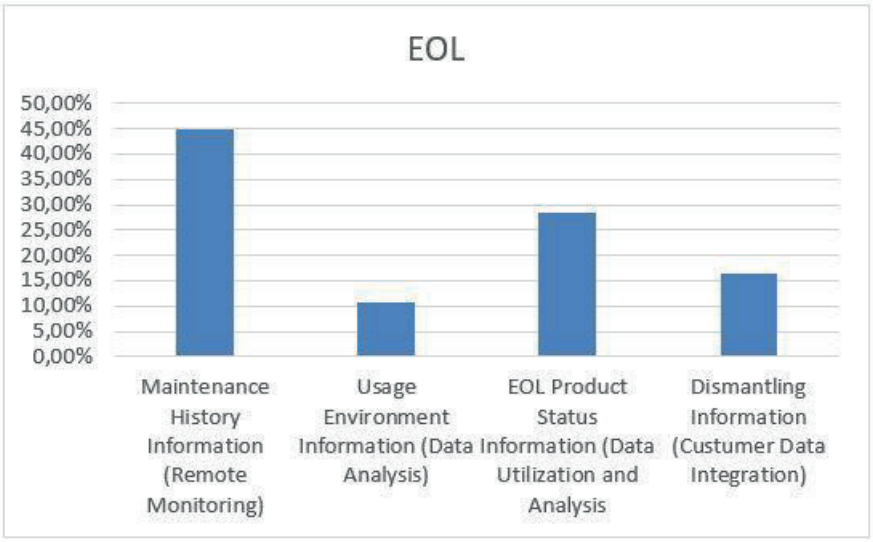

Fig. 13. Comparação gráfica atributos EOL.

A resolução do método AHP trouxe como resultado a Figura 14, classificando a empresa avaliada como nível 3, visto que a empresa se encontra com maior valor entre os níveis de maturidade.



Fig. 14. Resultado AHP (Nível de Maturidade).

Contudo, para elevar o nível de maturidade de 3 para 4, é aconselhável seguir algumas diretrizes, como otimizar no início do ciclo de vida do produto uma análise de dados relacionado à previsão de demanda de forma automatizada. Para a fase em que o produto já se encontra estabelecido, melhorar o manual do usuário, trazendo o cliente mais próximo do produto, com a utilização de uma linguagem acessível e com imagens ilustrativas ou a utilização de *QR Code* com vídeos de pessoas utilizando o produto. Para a fase final do ciclo de vida otimizar a integração com o cliente agrupando as informações desmanteladas sobre do produto e utilizar mais de 50% dos dados coletados.

5 Discussão e considerações finais

O estudo de caso revelou resultados promissores para a análise do nível de maturidade da organização através da abordagem proposta. Através do método AHP foi possível realizar comparações e diagnosticar atributos de maior relevância dentro de cada fase do ciclo de vida do produto (BOL MOL e EOL), tornando justificáveis em qual nível de maturidade do PLM com conceitos da indústria 4.0 a organização se encontra.

A empresa, sob nível 3 é caracterizada por ter um bom desenvolvimento de seu produto em todas as fases do ciclo de vida, porém pode otimizar seus resultados com maior utilização de dados obtidos. Na fase inicial do ciclo de vida do produto poderia ser trabalhada a aproximação do cliente e para as demais fases atuar agrupando as informações desmanteladas. Desta forma atende-se os seus clientes com respostas mais rápidas atuando na redução de custos sem perder a qualidade. Integrando cada vez mais o usuário com o produto é possível que a empresa consiga melhorar seu nível de maturidade.

Portanto após as melhorias sugeridas é possível que a empresa consiga ser classificada com nível 3 com tendência para o nível 4, atendendo seus clientes com respostas mais rápidas atuando na redução de custos sem perder a qualidade, aumentando sua competitividade e integrando cada vez mais o usuário com o produto.

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Desarrollo de herramientas para la gestión óptima de envases vacíos de fitosanitarios y sus contenidos residuales

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Abstract. En este trabajo se presenta un modelo de optimización multiperíodo para el diseño de un Sistema de Gestión Integral de Envases Vacíos de Fitosanitarios. El propósito es generar un esquema para la recolección de envases dentro del Sudoeste Bonaerense (SOB) y determinar las localizaciones óptimas para la instalación de Centros de Acopio Transitorio (CAT) y de Plantas Operadoras (OPR) de envases, conociendo la tasa de generación de envases en cada partido del SOB. La formulación propuesta considera la inversión y los costos operativos (fijos y variables) de cada CAT y OPR, así como los costos de transporte incurridos en la recolección de los envases y en el traslado a las plantas de procesamiento. Además, se incorpora la alternativa de realizar Campañas Itinerantes en las que los envases se transportan en forma directa desde los partidos a las plantas operadoras. El modelo matemático resultante corresponde a un Problema Mixto Entero Lineal (MILP) donde las decisiones discretas se emplean para determinar la instalación y uso de los CAT y OPR a lo largo del tiempo. El criterio de performance utilizado es la maximización del valor presente neto del sistema completo de gestión, teniendo en cuenta diferentes costos e ingresos por la venta del producto de las OPR. Los 4 escenarios estudiados arrojan resultados prometedores con un valor presente neto superior a USD 570.000 a lo largo de un periodo de 15 años.

Keywords: Fitosanitarios·Optimización·Modelo Mixto-Entero Lineal.

1 Introducción

Argentina cuenta con más de 36 millones de hectáreas cultivadas en las que se emplean casi 230 millones de litros de herbicidas y cerca de 350 millones de litros de agroquímicos [1]. Los envases necesarios para su comercialización generan unas 13.000 toneladas de polietileno de alta densidad (PEAD) cada año [2]. Particularmente, en la provincia de Buenos Aires se generan aproximadamente 5 millones por año de envases vacíos de agroquímicos [3]. Dentro del país los envases ya utilizados y sus contenidos residuales son considerados residuos peligrosos conforme la Ley Nacional de Residuos Peligrosos 24.051 [4]. En la actualidad, el manejo de estos envases se hace de diversas formas dependiendo del usuario. Tradicionalmente, los envases de agroquímicos vacíos han sido quemados, enterrados, reutilizados como contenedores para otros productos o bien tirados en canales de riego, ríos, arroyos, zanjas o campo a cielo abierto, generando focos de contaminación al medio ambiente y representando un peligro para la salud de personas y animales [5]. Los efectos por el uso de plaguicidas y sus envases reflejados en la salud de los usuarios directos, de la población expuesta indirectamente y los daños al ambiente, plantean la necesidad de medidas preventivas que garanticen el manejo seguro de estas sustancias [6].

Recientemente se sancionó la Ley Nacional 27.279 (Resolución N.° 327/17) [7], que establece los presupuestos mínimos de protección ambiental para la gestión de los envases vacíos de fitosanitarios, en virtud de la toxicidad del producto que contuvieron, requiriendo una gestión diferenciada y condicionada. Dicha Ley específica que el sistema se articulará en tres etapas: a) del Usuario al Centro de Acopio Transitorio, b) del Centro de Acopio Transitorio al Operador, c) del Operador a la Industria. Esta ley introduce el concepto de Responsabilidad Extendida y Compartida en la gestión de envases vacíos de agroquímicos. La misma asigna responsabilidades y establece obligaciones específicas a los distintos actores de la cadena. También es importante mencionar que el Art. N°5 apartado b) especifica que el tránsito inter-jurisdiccional no podrá ser prohibido por las provincias, pero si razonablemente reglamentado.

Múltiples esfuerzos para la gestión de envases de agroquímicos se han llevado a cabo en forma aislada tanto por municipios como por organizaciones no gubernamentales, sin obtener una solución concreta para el problema real. Aun se observan grandes falencias logísticas y de implementación, procesando una mínima cantidad de envases vacíos sin trazabilidad de su limpieza.

En este contexto, el presente trabajo presenta un estudio de gestión integral sostenible para los envases vacíos de fitosanitarios en el Sudoeste de la Prov. de Bs.As. Dicha región tiene como principal actividad productiva la producción agropecuaria. Además, su lejanía con respecto a las plantas operadoras localizadas en Cnel. Brandsen y en Lanús y su gran extensión territorial, representan un verdadero desafío a la hora de diseñar un plan eficiente de gestión para la recuperación de los envases vacíos de fitosanitarios. Como herramienta para el análisis se desarrolló un modelo matemático de optimización que permite estudiar los aspectos de diseño y operación de una red logística de recolección y disposición de dichos envases vacíos, teniendo como marco la Ley Nacional 27.279.

2 Formulación del problema

Teniendo en cuenta que la sostenibilidad es un pilar esencial para la gestión exitosa de los residuos, y que a su vez la misma se basa en tres aspectos fundamentales íntimamente relacionados entre sí, tales como la economía, la ecología y los aspectos sociales, este estudio se focaliza en la problemática asociada a los productores y municipios del Sudoeste de la Provincia de Buenos Aires (SOB).

El SOB se conforma con 22 partidos, 21 de los cuales tienen como principal actividad económica la producción agropecuaria. En el SOB se concentran 8 de los 27 Centros de Acopio Transitorio (CATs) instalados en la provincia de Buenos Aires y no posee ninguna planta operadora habilitada para lavar y procesar el plástico de los bidones [8,9]. En la Tabla 1 se listan los partidos que integran el SOB y se indica la capacidad de almacenamiento de envases vacíos de aquellos que poseen un CAT habilitado. En conjunto, los CATs habilitados tienen la capacidad para almacenar 89.000 envases de 20 litros, lo que representa aproximadamente un 6% del total de envases generados anualmente en el SOB.

Tabla 1. Partidos que conforman el sudoeste bonaerense

Partido	CAT (envases)	Partido	CAT (envases)
(1) A. Alsina		(12) Laprida	3.000
(2) A. G. Chávez		(13) Patagones	3.000
(3) B. Blanca		(14) Pellegrini	4.000
(4) B. Juárez	50.000	(15) Puan	10.000
(5) C. Dorrego		(16) Saavedra	4.000
(6) C. Pringles		(17) Salliqueló	
(7) C. Rosales		(18) Tornquist	
(8) C. Suarez		(19) Tres Arroyos	
(9) Daireaux	10.000	(20) Tres Lomas	
(10) Gral. la Madrid		(21) Villarino	5.000
(11) Guaminí			

Resulta importante para el diseño de un sistema de gestión integral contar con un diagnóstico actualizado de la localización geográfica, cantidad y tipo de envases que se generan en la región en estudio. La cantidad de envases se determinó a partir del área sembrada de cada cultivo extensivo y los protocolos de siembra aplicados a cada uno. Se realizó una regionalización del SOB en función del uso de fitosanitarios de acuerdo a las condiciones de suelo y el clima de cada región (ver Fig. 1). Los protocolos de siembra se consultaron a Extensionistas de las Agencias de INTA referentes de cada región: Bahía Blanca, Coronel Suárez y Tres Arroyos. Por otra parte, a partir los datos publicados por la Dirección Nacional de Análisis Económico Agroindustrial (Dirección de Estimaciones Agrícolas) en las Campañas 2008 a 2018 [10], se obtuvieron regresiones lineales, para estimar la superficie sembrada en el área de interés en función de los años a lo largo de en un periodo de 15 años. El número de envases de 20 litros que se genera por año en promedio en cada partido del SOB se muestra en el mapa de la Figura 1. En la misma se incluye la ubicación y capacidad de los CATs instalados actualmente,

como también la localización de las dos plantas operadoras y su capacidad de procesamiento de plásticos por año.

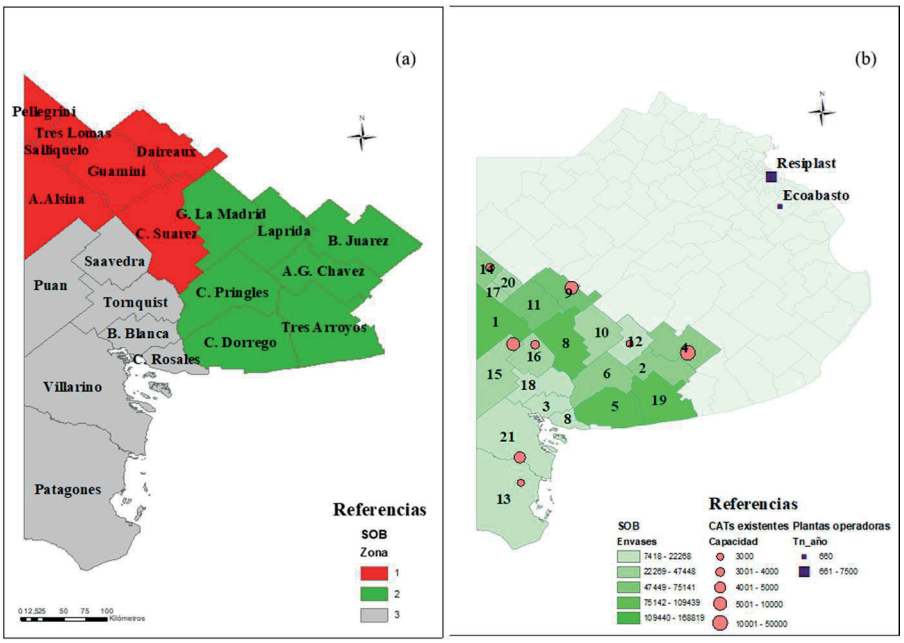

Fig. 1. Mapa del sudoeste bonaerense (SOB). (a) Regionalización del SOB por protocolo de siembra. (b) Envases generados en cada partido y ubicación de centros de acopio transitorio y plantas operadoras. Los partidos siguen la numeración provista en la Tabla 1. (Fuente: elaboración propia)

Una característica importante del SOB son las grandes distancias entre los lugares de generación del residuo y entre éstos y los centros de acopio y de tratamiento, por lo que resulta importante pensar adecuadamente los aspectos logísticos para generar un sistema integral de gestión de residuos que resulte práctico y eficiente.

3 Modelo matemático

El modelo consta de 34 ecuaciones para determinar la estructura óptima del problema de asignación de unidades de infraestructura con capacidades acotadas (CATs y OPRs), así como ecuaciones de costos fijos y operativos, en forma anual y a lo largo de un dado horizonte de tiempo.

La logística representa un costo significativo en cualquier plan de gestión de residuos, particularmente en las regiones en las que hay mucha distancia entre las áreas agrícolas y la zona de reciclaje y eliminación. Transportar envases vacíos es ineficiente, debido a la razón entre su gran volumen y su peso. Transportar los bidones enteros

consigue movilizar apenas un 20% de los kilos de plástico que pueden trasportase compactados. Los pre-tratamientos más utilizados para la disminución del volumen de los envases vacíos de fitosanitarios son la compactación y/o el triturado [11]. A diferencia del triturado de los envases, su compactado no afecta el proceso de reciclado que se lleva a cabo posteriormente en las plantas operadoras. En este trabajo se asume que la compactación solo se realiza en los CATs, donde se instalan equipos de prensado (enfardadoras), dado que es la opción que el Organismo Provincial para el Desarrollo Sostenible considera utilizar. Por lo cual, los bidones se transportan enteros desde los partidos hasta los CAT o desde los partidos hasta la planta operadora. Dentro del sistema de gestión, este último transporte constituye las campañas itinerantes de recolección de envases.

Dado que se trata de un problema de planificación a lo largo de un horizonte de tiempo, de la instalación de infraestructura necesaria para efectuar la recolección y tratamiento de los envases vacíos de fitosanitarios que se generan en el SOB, se elige como función objetivo maximizar el valor presente neto (VPN). Es necesario aclarar que, la instalación de al menos un CAT es una restricción del modelo. Esta restricción se incluye no solo por ser establecimientos definidos en el contexto de la Ley Nacional 27.279 sino también por constituir espacios que aseguran el correcto almacenamiento de los envases vacíos, desde el punto de vista de seguridad para las personas y cuidado del medio ambiente.

El modelo formulado es de tipo Mixto Entero Lineal (MILP). En la siguiente sección se presentan las definiciones de los diferentes conjuntos, parámetros (o datos) y variables enteras y continuas que definen el modelo.

3.1 Nomenclatura

Conjuntos

i	Partidos del SOB.
j	Centros de acopio transitorio (CAT).
t	Periodos del horizonte de planeación.
l	Plantas operadoras (OPR).

Parámetros

CAP	Costo del agua de proceso [USD/m^3].
CapcamC	Capacidad de carga vehículos de envases compactados [kg].
CapcamE	Capacidad de carga vehículos de envases enteros [kg].
$CAPreal_j$	Capacidad real de los CATs instalados en el SOB [envases].
CCj	Pendiente promedio de la curva de economías de escala del CAT j
CEE	Costo del MWh [USD].
CEnfar	Costo de compra de una enfardadora [USD].
CEsAP	Consumo especifico de agua en la planta operadora [m^3/t].
CEsEE	Consumo específico en la planta operadora [kWh/t].
CEsEEE	Consumo especifico de EE de la enfardadora [kWh/t].

c_{il}	Distancia entre el partido i y la planta operadora l [km].
$CMCAT_j$	Capacidad operativa máxima del CAT j ∈ J [envases/mes].
$CMOPR_l$	Capacidad operativa máxima de las OPRs l ∈ L [envases/período].
COCATfijo	Costo fijo de operación de cada CAT [USD/mes].
CT	Costo unitario de transporte de mercancías [USD/km].
CTA	Costo del tratamiento de agua [USD/m^3].
CTP	Costo unitario de transporte de residuos peligrosos [USD/km].
d_{ij}	Distancia entre el partido i y el CAT j [km].
ECOP	Costo de los equipos críticos planta operadora [USD].
Fadm	Factor costo fijo administrativo.
Fcomer	Factor costo fijo comercialización.
Fman	Factor costo fijo mantenimiento.
fr_t	Fracción de recuperación de envases en cada periodo t.
h_{it}	Envases del partido i en el período t [envases/período].
IAOP	Factor de costo de instalación y auxiliares de las OPRs [USD].
M	Valor utilizado para restricciones de tipo “Big-M”.
NC	Número máximo de CATs a instalar.
NCmin	Número mínimo de CATs a instalar.
NOP	Número máximo de plantas operadoras a instalar.
OOj	Ordenada al origen de la curva de economías de escala del CAT j.
P	Meses por periodo.
PE	Peso del envase de 20 L de HDPE [kg/envase].
Per	Cantidad de personas para operar la planta operadora.
Pr	Precio de venta de plástico HDPE [USD/t].
PTEL	Costo de la planta de tratamiento de efluentes [USD].
rec	Reciclo del agua de proceso.
r_{jl}	Distancia entre el CAT j y la planta operadora l [km].
S	Sueldo por persona [USD/periodo].
TR	Tasa de descuento de capital entre los períodos 1 y t.

Variables

Binarias

x_{jt}	Representa la operación del CAT j en el periodo t.
y_{lt}	Representa la operación de la OPR l en el periodo t.
$zCAT_j$	Representa la instalación de un CAT en j.
$zOPR_l$	Representa la instalación de una OPR en l.

Continuas

BEN_t	Beneficios netos en cada periodo t [USD/periodo].
$CICATamp_j$	Costo de ampliación de los CATs existentes [USD].
$CICAT_j$	Costo de inversión en j [USD].
$CIOPR_l$	Costo de inversión en l [USD].
$COCAT_{jt}$	Costo operativo de j en el periodo t [USD/ periodo].
$COCATtot_t$	Costo operativo de los CATs en cada periodo t [USD/ periodo].
$COOPRfijo_{lt}$	Costo fijo de la OPR l en el periodo t [USD/ periodo].
$COOPR_{lt}$	Costo operativo de l en cada periodo t [USD/ periodo].
$COOPRtot_t$	Costo operativo de las OPRs en cada periodo t [USD/ periodo].

$COOPRvar_{lt}$	Costo variable de la OPR l en el periodo t [USD/ periodo].
COP_t	Costos operativos totales en cada periodo t [USD/ periodo].
$COTRA_t$	Costo del trasporte en cada periodo t [USD/ periodo].
e_{ijt}	Envases enviados desde i al CAT j en t [envases/periodo].
f_{jlt}	Envases enviados del CAT j a la OPR l en t [envases/periodo].
g_{ilt}	Envases enviados desde i a la OPR l en t [envases/periodo].
ING_t	Ingresos totales en cada periodo t [USD/periodo].
$STCAT_{jt}$	Cantidad de envases en el CAT j en el periodo t [envases/periodo].
$STOPR_{lt}$	Cantidad de envases en la OPR l en el periodo t [envases/periodo].
$TSTCATextra_j$	Tamaño de ampliación requerida de CATs existentes [envases].
$TSTCAT_j$	Máx. N° de envases en el CAT j [envases/mes].
z	Variable objetivo.

Ecuaciones

A continuación, se presenta el modelo completo.

$$\text{Max } z = \sum_t BEN_t.(1+TR)^{-t} - \sum_j (CICAT_j + CICATamp_j) - \sum_l CIOPR_l \quad (1)$$

$$\sum_j x_{jt} \geq NCmin \quad \forall\, t \quad (2)$$

$$\sum_j x_{jt} \leq NC \quad \forall\, t \quad (3)$$

$$\sum_l y_{lt} \leq NOP \quad \forall\, t \quad (4)$$

$$x_{j\,t+1} \geq x_{jt} \quad \forall\, j,t \quad (5)$$

$$y_{l\,t+1} \geq y_{lt} \quad \forall\, l,t \quad (6)$$

$$zCAT_j \geq x_{jt} \quad \forall\, j,t \quad (7)$$

$$zOPR_l \geq y_{lt} \quad \forall\, l,t \quad (8)$$

$$fr_t \,.\, h_{it} = \sum_j e_{ijt} + \sum_l g_{ilt} \quad \forall\, i,t \quad (9)$$

$$\sum_i e_{ijt} = \sum_l f_{jlt} \quad \forall\, j,t \quad (10)$$

$$e_{ijt} \leq M.x_{jt} \quad \forall\, i,j,t \quad (11)$$

$$f_{jlt} \leq M.y_{lt} \quad \forall\, j,l,t \quad (12)$$

$$\sum_i e_{ijt} = STCAT_{jt} \quad \forall\, j,t \quad (13)$$

$$STCAT_{jt} \leq M.x_{jt} \quad \forall\, j,t \quad (14)$$

$$\sum_j f_{jlt} + \sum_i g_{ilt} = STOPR_{lt} \quad \forall\, l,t \quad (15)$$

$$STOPR_{lt} \leq M.y_{lt} \quad \forall\, l,t \quad (16)$$

$$STCAT_{jt}/P \leq TSTCAT_j \quad \forall\, j,t \quad (17)$$

$$TSTCATextra_j = TSTCAT_j - CAPreal_j \quad \forall\, j \quad (18)$$

$$TSTCAT_j \leq M.zCAT_j \quad \forall\, j \quad (19)$$

$$STOPR_{lt} \leq CMOPR_l \quad \forall\, l,t \quad (20)$$

$$TSTCAT_j \leq CMCAT_j \quad \forall\, j \quad (21)$$

$$CICAT_j = OOj.zCAT_j + CCj.TSTCAT_j + CEnfar.zCAT_j \quad \forall\, j \quad (22)$$

$$CICATamp_j = OOj.zCAT_j + CCj.TSTCATextra_j + CEnfar.zCAT_j \quad \forall\, j \quad (23)$$

$$CIOPR_l = ((1+IAOP).ECOP + PTEL).zOPR_l \quad \forall\, l \quad (24)$$

$$COCAT_{jt} = x_{jt}.COCATfijo.P + CEsEEE.CEE.STCAT_{jt}.PE.1.10^{-6} \quad \forall\, j,t \quad (25)$$

$$COOPRvar_{lt} = \frac{STOPR_{lt}}{1000}.PE.(CEE.CEsEE + CAP.CEsAP.(1-rec) + CEsAP.CTA) \quad \forall\, l,t \quad (26)$$

$$COOPRfijo_{lt} = \frac{STOPR_{lt}}{1000}.PE.Pr.(Fadm + Fcomer) + Per.S.zOPR_l + CIOPR_l.Fman \quad \forall\, l,t \quad (27)$$

$$\mathrm{COOPR_{lt}} = \mathrm{COOPRfijo_{lt}} + \mathrm{COOPRvar_{lt}} \qquad \forall\, l, t \qquad (28)$$

$$\mathrm{COCATtot_t} = \sum_j \mathrm{COCAT_{jt}} \qquad \forall\, t \qquad (29)$$

$$\mathrm{COOPRtot_t} = \sum_l \mathrm{COOPR_{jt}} \qquad \forall\, t \qquad (30)$$

$$\mathrm{COTRA_t} = \mathrm{CT}.\left(\sum_i \sum_j \frac{e_{ijt}.d_{ij}.PE}{CapcamE}\right) + \mathrm{CTP}.\left(\sum_i \sum_l \frac{g_{ilt}.c_{il}.PE}{CapcamE} + \sum_j \sum_l \frac{f_{jlt}.r_{jl}.PE}{CapcamC}\right) \qquad \forall\, t \qquad (31)$$

$$\mathrm{COP_t} = \mathrm{COTRA_t} + \mathrm{COCATtot_t} + \mathrm{COOPRtot_t} \qquad \forall\, t \qquad (32)$$

$$\mathrm{ING_t} = \mathrm{Pr}.\sum_l \frac{\mathrm{STOPR_{lt}}}{1000}.\mathrm{PE} \qquad \forall\, t \qquad (33)$$

$$\mathrm{BEN_t} = \mathrm{ING_t} - \mathrm{COP_t} \qquad \forall\, t \qquad (34)$$

La Ecuación (1) es la función objetivo que maximiza el valor presente neto del problema de instalación de CATs y OPRs y de transporte de los envases. Las Ecuaciones (2) a (8) son las ecuaciones lógicas para la determinación de la localización de los CATs y OPRs. Las Ecuaciones (9) a (21) determinan el tamaño de los envíos de los partidos a los CATs, de los CATs a las OPRs y de los partidos a las OPRs. También determinan el stock por mes de cada CAT y por año de cada OPR. Las Ecuaciones (22) a (32) calculan los costos anuales de inversión, operativos y de transporte. La Ecuación (33) calcula los beneficios anuales de la venta del plástico procesado y la Ecuación (34) calcula los beneficios netos cada año.

El modelo se implementó y resolvió con el programa GAMS 24.2.3 (General Algebraic Modeling System) [12], con CPLEX 12 como programa de resolución del modelo MILP. Los resultados que se presentan en la siguiente sección se obtuvieron en una computadora con procesador Intel(R) Core (TM) i7-85500, 2,00 GHz y una memoria RAM de 16GB.

4 Resultados

El modelo matemático se aplica para la resolución de dos escenarios, cada uno con dos alternativas. El Escenario 1 es el de una situación en la que se diseña desde cero la red de CATs y OPRs, donde se determina en forma óptima la cantidad y ubicación de estas unidades, así como la asignación del envío de los envases desde los partidos a los CATs y/o OPRs, y desde los CATs a las OPRs. Además, se impone que al menos se instale un CAT. El propósito del Escenario 1 es tener una referencia y compararlo con el Escenario 2, que consiste esencialmente en el mismo problema, pero si bien se pueden ubicar unidades adicionales con su correspondiente costo de instalación y de operación, se respeta la cantidad y ubicación de los CATs y OPRs ya existentes, por lo que para ellos no se considera su costo de instalación. En total para este escenario hay 8 CATs instalados y 2 plantas operadoras ubicadas en los partidos de Brandsen y Lanús, en la Provincia de Buenos Aires, pero fuera de la región SOB (ver Figura 1).

Ambos escenarios se dividen en dos situaciones, en la primera (Escenarios 1a y 2a) se considera que el 100% de los envases que se generan en el SOB se alimentan al sistema de recuperación de envases, mientras que en la segunda situación (Escenarios 1b y 2b) esta alimentación se realiza en forma gradual desde el primer periodo hasta el último. En la Fig. 2 se muestra un esquema general del problema a resolver.

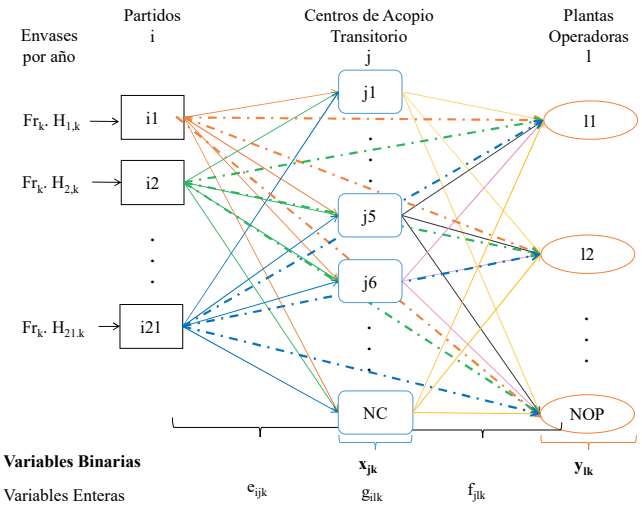

Fig. 2 Esquema general de los escenarios estudiados en este trabajo. (Fuente: elaboración propia)

Para los cuatro escenarios, el tamaño del modelo indica que se trata de un problema relativamente chico tanto en variables continuas como binarias como se observa en la Tabla 2. En la Tabla 3 se puede observar que las soluciones se alcanzan en tiempos de CPU del orden de uno a dos minutos, lo cual es razonable en relación al tamaño de los problemas. En esta tabla se observa además que el esfuerzo computacional de resolución es menor en los casos donde el porcentaje de recuperación de envases aumenta con los años (E1b y E2b). También se presentan los tiempos empleados para alcanzar el valor final de la función objetivo, que se ve son mucho menores a los tiempos necesarios para lograr el gap cero en todos los escenarios, lo que sugiere que los tiempos de cómputo podrían reducirse sustancialmente si fuera necesario, fijando un gap mayor para convergencia y sin que eso implique un deterioro de la función objetivo.

Tabla 2. Tamaño de los modelos empleados para describir los escenarios estudiados en este trabajo

Escenario	Variables binarias	Variables continuas	Ecuaciones	Desigualdades
E1 a y b	768	26053	3709	17367
E2 a y b	768	26095	3751	17367

Tabla 3. Resumen de los tiempos de cómputo de los escenarios estudiados en este trabajo y valor de la función objetivo obtenida para cada uno

	E1a	E1b	E2a	E2b
CPU GAP=0 (s)	68,734	44,703	435,406	57,922
CPU solución (s)	34,61	39	317	1,36
Función objetivo (USD)	4.337.487	771.367	3.883.426	570.295

Como puede observarse en la Tabla 3, para todos los escenarios estudiados el VPN es positivo y superior a 570.000 USD indicando que el sistema de gestión integral de envases vacíos de agroquímicos propuesto para cada caso resulta atractivo económicamente. El VPN del Escenario 2a es del orden del 90% del correspondiente al Escenario 1a, cuando el 100% de los envases forman parte del sistema de gestión; mientras que el VPN del Escenario 2b es un 75% del obtenido para el Escenario 1b. Esto sugiere que, si el sistema opera con menor cantidad de envases, lo hace más alejado del escenario de referencia óptimo. Además, para ambos escenarios, el VPN de las alternativas b es apenas el 20% de las alternativas a.

La localización óptima de los CATs y de las plantas operadoras para cada escenario se indican en las Tablas 4 a 7 , además se incluye el costo de instalación de los mismos y la cantidad máxima de envases que se reciben y procesan respectivamente. Debido a que el número de envases generados en el SOB crece a lo largo del horizonte de tiempo de estudio, la capacidad máxima de la planta operadora tiene lugar en el último período, al igual que la ocupación máxima de los CATs en los Escenarios 1b y 2b ya que la incorporación de envases al sistema es gradual y se incrementa con el tiempo. Para los Escenarios 1a y 2a, los CATs operan en su capacidad máxima desde el primer período estudiado. Además, es importante destacar que el costo de inversión de la planta operadora es el mismo para todos los escenarios, esto se debe a que la cantidad anual de envases vacíos generados en el SOB, es menor a la capacidad mínima de las tecnologías de procesamiento de plástico comúnmente empleadas para el reciclado del PEAD de estos contenedores.

Tabla 4. Resultados para el escenario 1a

Localización de los CATs	Costo de inversión (USD)	Ocupación mensual (máx. envases)
J19: Tres Arroyos	193.538	41.483
Localización de las OPRs	**Costo de inversión (USD)**	**Ocupación anual (máx. envases)**
L11: Guaminí	745.237	1.593.637

CATs: Centros de Acopio Transitorio, OPRs: Plantas Operadoras

Tabla 5. Resultados para el escenario 1b

Localización de los CATs	Costo de inversión (USD)	Ocupación mensual (máx. envases)
J19: Tres Arroyos	82.181	14.469
Localización de las OPRs	**Costo de inversión (USD)**	**Ocupación anual (máx. envases)**
L8: Coronel Suarez	745.237	1.434.274

CATs: Centros de Acopio Transitorio, OPRs: Plantas Operadoras

Tabla 6. Resultados para el escenario 2a

Localización de los CATs	Costo de inversión (USD)	Ocupación mensual (máx. envases)
J4: Benito Juárez		37.460
J9: Daireaux		10.000
J12: Laprida		3.000
J13: Patagones		2.482
J14: Pellegrini	28.025 (ampliación)	10.045
J15: Puan	14.440 (ampliación)	13.114
J16: Saavedra	5.543 (ampliación)	5.195
J21: Villarino		5.000
Localización de las OPRs	Costo de inversión (USD)	Ocupación anual (máx. envases)
L8: Coronel Suarez	745.237	1.593.637

CATs: Centros de Acopio Transitorio, OPRs: Plantas Operadoras

Tabla 7. Resultados para el escenario 2b

Localización de los CATs	Costo de inversión (USD)	Ocupación mensual (máx. envases)
J4: Benito Juárez		50.000
J9: Daireaux		10.000
J12: Laprida		3.000
J13: Patagones		3.000
J14: Pellegrini	14.204 (ampliación)	7.404
J15: Puan		10.000
J16: Saavedra	4.277 (ampliación)	5.025
J21: Villarino		5.000
Localización de las OPRs	Costo de inversión (USD)	Ocupación anual (máx. envases)
L27: Brandsen	0	1.434.274

CATs: Centros de Acopio Transitorio, OPRs: Plantas Operadoras

Para facilitar la visualización de los resultados obtenidos, las Figuras 3 a 6 muestran el esquema óptimo de asignación de Partidos-CATs-OPRs que deben seguir los envases vacíos de fitosanitarios para cada uno de los escenarios estudiados en este trabajo. En cada figura se puede notar como se modifica el esquema a lo largo del horizonte de tiempo estudiado, las Figuras 3 a 6 (a) corresponden al primer período y las Figuras 3 a 6 (b) al último.

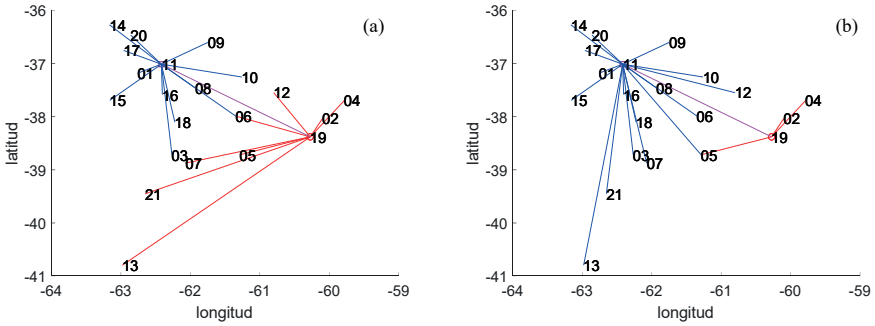

Fig. 3. Escenario 1a, (a) primer período (b) último período. Las líneas rojas indican los partidos que se asignan a las unidades de CATs seleccionados por el modelo, las magenta corresponden a las asignaciones de los CATs a las OPRs y las líneas azules indican las campañas itinerantes. Los partidos siguen la numeración provista en la Tabla 1. (Fuente: elaboración propia)

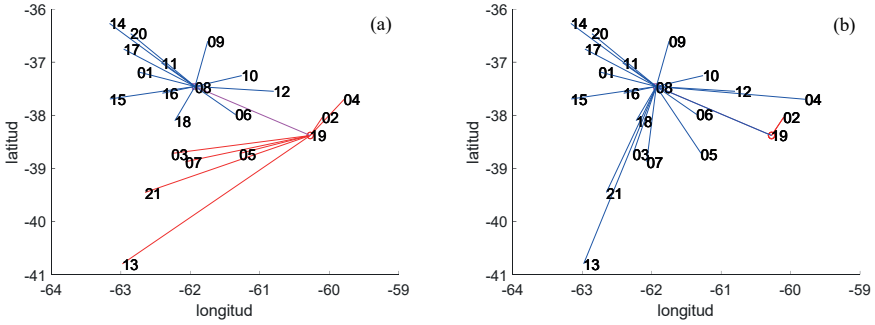

Fig. 4. Escenario 1b (a) primer período (b) último período. Las líneas rojas indican los partidos que se asignan a las unidades de CATs seleccionados por el modelo, las magenta corresponden a las asignaciones de los CATs a las OPRs y las líneas azules indican las campañas itinerantes. Los partidos siguen la numeración provista en la Tabla 1. (Fuente: elaboración propia)

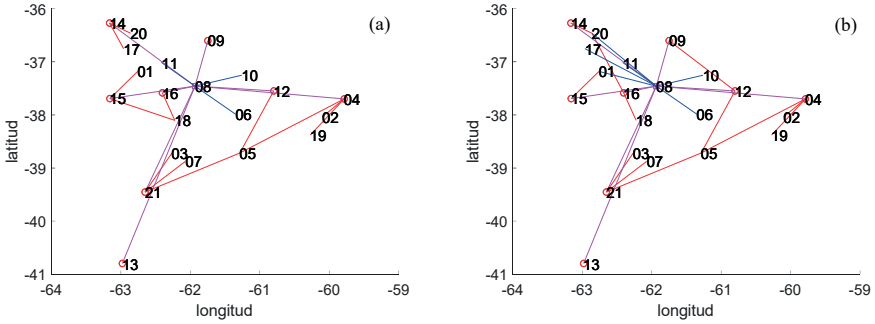

Fig. 5. Escenario 2a (a) primer período (b) último período. Las líneas rojas indican los partidos que se asignan a las unidades de CATs seleccionados por el modelo, las magenta corresponden a las asignaciones de los CATs a las OPRs y las líneas azules indican las campañas itinerantes. Los partidos siguen la numeración provista en la Tabla 1. (Fuente: elaboración propia)

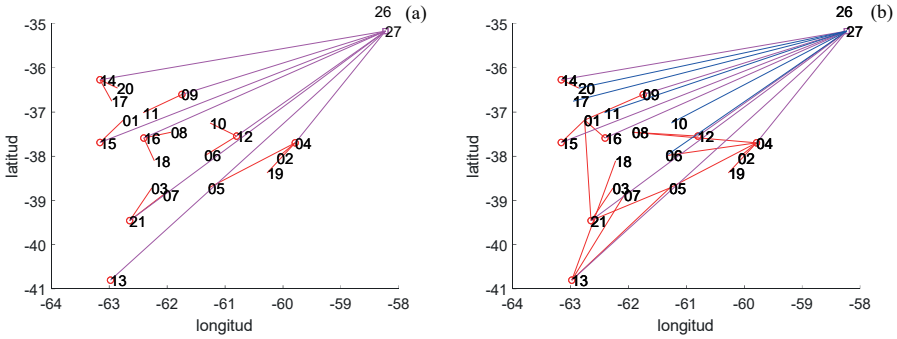

Fig. 6. Escenario 2b (a) primer período (b) último período. Las líneas rojas indican los partidos que se asignan a las unidades de CATs seleccionados por el modelo, las magenta corresponden a las asignaciones de los CATs a las OPRs y las líneas azules indican las campañas itinerantes. Los partidos siguen la numeración provista en la Tabla 1, 26 y 27 representan las plantas operadoras de Lanús y Brandsen respectivamente. (Fuente: elaboración propia)

En particular, como resultado de la optimización del escenario de referencia, es decir, sin tener en cuenta los CATs que se encuentran actualmente instalados en el SOB, el modelo sugiere instalar un CAT y una OPR en el SOB. Independientemente de la oferta de envases (escenarios a y b). En el caso en que todos los envases generados en el SOB se integren al sistema de gestión integral desde el primer año, el modelo sugiere la instalación de un único CAT con capacidad para 42.000 envases en Tres Arroyos. En el caso en el que la incorporación de los envases al sistema sea progresiva, el CAT también se instala en Tres Arroyos, pero tiene una capacidad menor, menos de la mitad. En ambos casos, alrededor de 8 partidos envían sus envases al CAT como puede observarse en la Figuras 3 y 4. A lo largo del horizonte de tiempo, como se muestra en las figuras, para ambos escenarios se incrementa el número de campañas itinerantes. La localización de la planta operadora es distinta para los dos escenarios, en el escenario 1a se instala en Guaminí mientras que en el escenario 1b se instala en Coronel Suárez. Esto se debe a la alimentación progresiva de envases en el tiempo que tiene lugar en el Escenario 1b. En esta situación, es más rentable instalar un CAT de menor capacidad en Tres Arroyos y realizar más campañas itinerantes en los años que sea necesario. En consecuencia, para reducir los costos de transporte, el modelo decide instalar la planta operadora 68 km al sudeste de Guaminí (localización de la planta operadora del E1a), en un punto central geográficamente del SOB. Este efecto puede visualizarse comparando las Figuras 3 y 4.

Por otro lado, los resultados para el escenario 2 indican que no se instalan nuevos CATs, si no que conviene ampliar los existentes. Sin embargo, la capacidad de almacenamiento total en el Escenario 2a disminuye en un 3% respecto a la capacidad instalada en la actualidad (Tabla 1), lo que sucede es que el CAT ubicado en Benito Juárez no se ocupa su totalidad. Por otro lado, en el Escenario 2b la capacidad de almacenamiento de envases vacíos se incrementa en apenas un 5%, en ambos escenarios lo que ocurre es que principalmente aumenta la capacidad relativa de los CATs que se ubican en la zona noroeste del SOB y en particular es el CAT ubicado en Pellegrini el que aumenta de forma más significativa su capacidad. Como puede observarse en la Figura

5 el número de campañas itinerantes se duplica a lo largo del tiempo para el Escenario 2a y a partir de la Figura 6 se puede notar que en el caso del Escenario 2b aparecen recién en el último período, representando apenas la mitad que en el Escenario 2a. En el escenario 2a se instala una planta operadora en el partido de Coronel Suárez, mientras que para el escenario 2b, los envases son enviados a la planta existente en Brandsen. Este resultado muestra que, mientras el factor de recuperación de envases en el SOB sea cercano al 100% es conveniente invertir en una planta operadora en lugar de utilizar la de la localidad de Coronel Brandsen, como se obtiene en el escenario 2b, donde el factor de recuperación de envases aumenta de forma gradual a lo largo del horizonte de planificación.

Una de las principales características de los problemas logísticos es la incertidumbre en los datos [13,14]. En particular en la logística de envases fitosanitarios vacíos la oferta de los mismos es uno de tales datos críticos dado que no se dispone de registros oficiales de los mismos [15,16]. Por este motivo se realizó un análisis de sensibilidad alrededor de la solución nominal (fijando las variables binarias) para los 4 escenarios, considerando una variación de ± 30% en los envases a recolectar. Los resultados indican una importante sensibilidad en este parámetro ya que una variación del 30 % en la cantidad de envases disponibles influye en un 40 % en el VPN en el escenario 1a, en un 85 % en el escenario 1b y en un 100 % en el escenario 2b. En el caso del escenario 2a, solo se realizó un análisis de sensibilidad de entre el + 10% y + 30% ya que en el caso de que la oferta disminuyera, el modelo localiza la planta en Cnel. Brandsen.

5 Conclusiones

Los resultados del trabajo indican que las alternativas estudiadas para la gestión de la recolección de envases vacíos de fitosanitarios resultan rentables con valores del VPN superiores a los 570.000 USD a 15 años.

Además, se logra cuantificar la importancia de la concientización, difusión y capacitación constante acerca del sistema de gestión integral para lograr el desarrollo de una economía circular entorno al mercado de agroquímicos en el sudoeste bonaerense, como así también, la importancia de determinar fehacientemente la cantidad de envases para que el diseño del sistema sea confiable. El VPN de los Escenarios 1b y 2b disminuye drásticamente en un 80% respecto a las alternativas 1a y 2a en las que el 100% de los envases vacíos generados en el SOB se alimentan al sistema de gestión integral.

Los resultados del modelo para los Escenarios 2 a y b que tienen en cuenta los CATs actualmente instalados, indican que se requiere la ampliación de la capacidad de almacenamiento de envases vacíos de los CATs ubicados en el noroeste del SOB para optimizar el funcionamiento del sistema de gestión integral. También se puede notar la importancia de las campañas itinerantes como herramienta para el buen desempeño del sistema de recupero de envases vacíos.

Otro aspecto interesante para destacar es que para el Escenario 2a que considera que el total de los envases generados en la región se alimentan al sistema de gestión, el modelo indica como óptima la instalación de una planta operadora en Coronel Suárez un partido muy productivo y ubicado en el centro geográfico del SOB. Si en cambio, la

incorporación de los envases es gradual, es más conveniente económicamente enviar los envases del SOB a procesar a la planta existente en Brandsen. Este aspecto también se demuestra mediante el análisis de sensibilidad. Se podría concluir que el esfuerzo conjunto de todos los actores de la cadena de comercialización de agroquímicos del SOB podría tener como resultado un importante impacto en el desarrollo de la región.

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Operation Skipping Flow Shop Scheduling and Industry 4.0

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Abstract. Industry 4.0 is a modern approach where the connectivity between different stages of the production process and the consumers is enhanced. In this paper a relevant problem for both Industry 4.0 and flow shop literature is addressed: an operation skipping flow shop scheduling problem. A solution method to optimize total tardiness, which is novel to the related literature, is presented. The solution approach consists of two stages. In the first stage, a genetic algorithm is applied to obtain an efficient solution in a permutation fashion. In the second stage, the solution obtained in the previous stage is improved with a simulated annealing algorithm considering a non-permutation strategy. Results show that NPFS solutions outperform PFS solutions for this problem. Furthermore, if the percentage of skipping operations increases the impact of the NPFS approach increases too.

Keywords: Industry 4.0, Non-Permutation Flow Shop, Skipping Operations, Cyber-Physical System.

1 Introduction

The conceptual model Industry 4.0 enhances connectivity between the different components of the production systems, as well as among the components and the decision-making centers [1] [2]. This allows production planners to manage information in real time from the shop floor [3]. This communication increases the flexibility of the production system since the machines have the capacity to communicate with each other and with the decision-making centers [4], allowing designs of innovative products with increasing adaptability. Moreover, given the high level of digitalization and through IIoT (Industrial Internet of Things), it is possible to offer mass customization of products as a business strategy, i.e., the production process can be adjusted so that the final products meet the specific customer requirements. In other words, for a given product

each customer can choose among different combinations of optional features, configurations or characteristics in such a way that the final product is highly personalized [5]. However, these personalized products are translated into specific production activities in the production line. Therefore, efficient scheduling techniques that can manage this variability should be applied in the production line to meet the specifications of each customer in the Industry 4.0 production environment [6].

Currently, one of the most widespread and efficient production configurations is the manufacturing cell. The manufacturing cell represents a set of production resources or machines that are grouped by the type of products they produce and organized in sequential mode [7]. The resulting output of a machine is transformed into the input of the next machine, and this happens with each of the machines in the cell. Generally, this type of configurations is considered within the flow shop scheduling family of problems [8] [9]. Product customization powered by Industry 4.0 will have a significant impact on this type of problem [5]. Given the freedom provided to the customer when customizing a product, it is very likely that, when following the customer specifications, the operations that must be performed to produce this product imply different uses of the machines in the cell. Thus, some of the operations introduced in the cell design may not be required to achieve the specifications requested by customers [9], these are the missing or skipping operations.

In the related literature, problems of flow shop with skipping operations for many productive environments have been studied [10]. In the vast majority of these works, the problems are solved by considering only permutation solutions (PFS) [11], meaning that the works are processed by each machine in the same order. In terms of search space, this entails finding the best solution in a universe of $n!$ possible solutions, being n the number of jobs to be processed. However, this condition of permutativity is not a technological constraint of the production process, since, in general, machines can process works in any order. It is only a condition introduced for reducing the complexity of the scheduling process. Therefore, another approach to solve these problems is based on relaxing this condition of permutativity, which involves solving the problem under the non-permutation approach (NPFS) [12]. In this approach, the job sequence for each machine can be modified, increasing the search space considerably from n to $n!^m$ solutions, where m is the number of machines [13]. Since NPFS solutions include PFS solutions as a particular case, NPFS solutions are at least as efficient as PFS if not more efficient, and it has been demonstrated that PFS are usually outperformed by NPFS in regard to the objective function values [10] [13]. Despite the industrial interest in this problem, NPFS has not yet been addressed for systems that contemplate Industry 4.0 production environments [3]. This article applies metaheuristics to solve PFS and NPFS, following the aforementioned approach.

Although results in the related literature show that NPFS solutions tend to outperform PFS solutions when considering objective functions related to delivery dates [13], the NPFS with skipping operations considering such optimization criteria has not been studied until now [14]. Therefore, this work makes a contribution and aims at providing a solution approach for considering PFS and NPFS solutions in this kind of problem.

2 Problem Definition

In this section, we properly introduce the problem studied in this work. Firstly, we analyze the impact of Industry 4.0 in manufacturing cells and how this influences the exchange with the customer. Then, we define our conception of the problem, relating our approach to the scheduling literature.

2.1 Industry 4.0 Environment

Industry 4.0 proposes a digital transformation of traditional production systems [2]. This transformation is based on the implementation of cyber-physical systems (CPS), which integrate virtual and physical processes in the same system [15]. Moreover, through IoT, CPS can communicate with each other and with the Decision Support Systems, which in terms of production planning, means to allow directly linking the shop floor with the support systems for production decision making [15] [4]. On the other hand, CPS allows generating a digital twin of the physical system [16], to analyze situations and making decisions more agilely and with more information than in a traditional production system. This results in a much more flexible production system, better adapted to different scenarios [17]. This way, the manufacturing system becomes smart, being able to provide an improved service to the customer, satisfying its needs in a personalized way [1]. This allows bringing the final product closer to the true requirements of the customer, who is actively involved in the design of the product [17].

The customer expresses his/her preferences by specifying different variants of a base product belonging to a given family of products, configuring what is known as a personalized variant of the product [18]. In this way, by making the production system more flexible, and making it smart, Industry 4.0 allows to offer to the customer a much higher level of personalization than in traditional production systems [19] [20].

The problem addressed in our work responds to these conditions imposed by Industry 4.0 in manufacturing cell systems. Given that the focus when solving the problem is on providing the best possible level of service to the customer, it is appropriate to study scheduling performance metrics related to service level, such as total tardiness.

2.2 Flow shop Scheduling in Manufacturing

The problem considered in this work can be described as to schedule production for a set of products that share production resources, with the feature that all products use the same resources maintaining the same technological sequence, i.e., a flow shop scheduling problem [8]. However, considering the scenario of intensive personalization promoted by Industry 4.0 [2], each product will have its particularities, a fact that will imply a different use of resources, which is generally expressed in varying processing times. This difference in use can even imply that, directly, the product does not use one of the resources of the manufacturing cell, which means that the product skips that operation (skipping operations flow shop scheduling problem) [21]. Therefore, the objective is to schedule production in such a way that the highest service level is achieved,

complying with the delivery dates. For this, we will seek to minimize the cumulative delays in the delivery of the products.

On the other hand, this problem can be addressed by considering only permutation solutions (Permutation Flow Shop, PFS), or by considering non-permutation solutions (Non-Permutation Flow Shop, NPFS) [9] [14]. In the first case, PFS, the solution search space includes those sequences represented by the possible permutations of the n jobs, that is, a total of $n!$ feasible solutions. Whereas if the job ordering is allowed to be modified for each stage of the flow shop, i.e. NPFS, the space of solutions grows to $n!^m$, where m is the number of machines. These problems are identified in the classic notation for scheduling problems [22] as *F|prmu/missing|TTard* and *F|missing|TTard*, respectively.

Therefore, the problem to be solved is to sequence the jobs in such a way that, complying with the precedence relationships among the operations, the objective function is minimized. If π is a permutation sequence, that implies that once job j was processed before job j', then, j will precede job j' on all machines. Therefore, to minimize the objective function, the permutation version seeks that the order π of the jobs, allows the completion times of each job, C_j, to exceed as little as possible the delivery date of each job d_j. In other words, the tardiness for each job j is as small as possible. Where the tardiness for job j is: $T_j = max\{C_j - d_j, 0\}$. Then the objective function can be expressed as:

$$\min_{\pi} \sum_j T_j(\pi) \tag{1}$$

For the non-permutation case, the objective function is the same, but the order π' is considered, which allows changes of precedence relationships among jobs. For instance, for π', job j can precede job j' up to machine i, and from machine $i + 1$ onwards, j' can precede j.

3 Solution approach

To solve the problem under study two metaheuristic algorithms were used in a sequential fashion. First, a Genetic Algorithm (GA) is used to optimize this problem considering only PFS solutions. Then, the best solution obtained by the genetic algorithm is used as the initial solution for the second algorithm. This second phase is a Simulated Annealing Algorithm (SA) that aims at improving the solution by considering NPFS solutions. The main characteristics of both algorithms are presented below.

3.1 Genetic Algorithm

For solving the PFS problem introduced in Section 2, a steady state Genetic Algorithm (ssGA) is proposed. ssGA is known to be a valid choice in problems where fitness evaluation is computationally expensive [23] and, thus, in flowshop problems (see, e.g., [24]). The proposed algorithm was implemented in Java, by using JMETAL framework [25] version 4.5.2. This algorithm has the following features.

Solution representation. Solutions are encoded as a permutation of integers of length equal to the number of jobs n. Each index in the vector represents the processing order in the (first) machine and the corresponding integer value represents the job.

Initialization. The population of size $\#P$ is initialized by applying a random procedure to generate the permutations using a uniform distribution.

Genetic operators. The recombination operator is the Partially Mapped Crossover (PMX) applied over two selected individuals with probability p_c. The mutation operator is based on Swap Mutation and interchanges two elements of the permutation. The Mutation operator is applied to an individual with probability p_m. The proposed operators guarantee the feasibility of the solution.

Selection, replacement, and fitness assignment. Tournament selection is applied, with tournament size of two solution representations. The tournament criterion is based on the fitness, and if two compared individuals have the same fitness, either of the two is chosen with equal probability. The new individual replaces the worst individual in the population if it has better fitness.

Parameters setting. The parametrization was performed with a statistical analysis considering three main parameters: population size $\#P$, crossover probability p_c and mutation probability p_m. The values considered were 100 and 200 for $\#P$; 0.7, 0.8, 0.9 and 1 for p_c; and 0.05 and 1 for p_m. The maximum number of evaluations used for the parametrization was 5000. The parameter setting analysis was made using three instances of size n =15 and m = 20, different from the scenarios used for the computational experimentation of Section 5. For each instance and each parametric combination ($\#P$, p_c, and p_m), 30 independent runs where performed. Shapiro-Wilk test was applied to assess if the fitness values follow a normal distribution. Since several of the runs did not adjust to the normal distribution, the medians were analyzed and the final parametric combination that was selected was $\#P$ = 100, p_c = 0.7 and p_m = 0.05.

3.2 Simulated Annealing algorithm

In this section, the simulated annealing algorithm used to solve the problem presented previously is described.

Simulated Annealing (SA) is a local search-based method that was developed from an analogy with the phenomenon of annealing [26] to solve complex optimization problems. Local search methods look for the solution with the best value of the chosen criterion in the neighborhood of the current solution, accept it as the current solution, and repeat this step until it is not possible to improve the solution in the explored neighborhood. By systematically applying this procedure, in general, a local optimum for the problem is obtained. To avoid getting trapped at a local optimum, a diversifying mechanism should be incorporated with the aim of exploring the entire solution space. In the simulated annealing metaheuristic, the diversifying strategy allows moves, with a certain probability, toward solutions that worsen the current value of the objective function. SA has shown competitiveness in handling regular flow shop environments [13] and also NPFS with missing operations [8].

In a minimization problem, the simulated annealing algorithm evolves from one candidate solution to the next, considering the behavior of the objective function value

following to the subsequent procedure. If the newly generated candidate solution (S_C) which is in the vicinity of the current solution ($S_C \in V(S_A)$] has a smaller objective function value than the current solution, i.e., $z(S_C) \leq z(S_A)$, the candidate solution is accepted as the current solution. Conversely, if $z(S_C) > z(S_A)$, a probabilistic test known as the Metropolis criterion is used to determine the probability of accepting a relatively lower quality solution. This means, that this sequence can be accepted with a certain probability $P(A) = e^{-\Delta z/T}$. Thus, $P(A)$ decreases as the difference between the objective function values of both solutions increases. T is the control parameter that simulates the role of the temperature in the physical process of annealing. If the candidate solution is not accepted, another sequence is selected randomly and the procedure is repeated.

4 Results

The experimental evaluation was aimed at evaluating appropriately the PFS and NPFS approaches to solve the skipping operations flow shop scheduling problem. This Section presents the instances and the experimental design that were used to assess the algorithms and describes the results obtained by applying both algorithms, making a comparison between the PFS and NPFS solution approaches.

4.1 Instances and Experiment design

For generating the test instances, we have taken as reference previous works that have considered NPFS with missing operation [8] and those that considered due-date related objective functions [27] [28]. The main parameters of the instances are the processing times of each job in each machine ($p_{i,j}$). In general, $p_{i,j}$ values are simulated using a uniform distribution within the interval [1; 99]. However, since this paper considers the possibility of job skipping machines (or operations), it is necessary to incorporate the 0 within that distribution. Furthermore, since this experiment aims at testing the algorithms in instances with a significant proportion of missing operations, a pseudo-uniform distribution is implemented where the probability assigned to $p_{i,j} = 0$ is greater than the probabilities for the rest of the possible interval values. Thus, by defining different values for the probability of occurrence of $p_{i,j} = 0$ within this pseudo-uniform distribution, it is possible to generate diverse instances with different proportions of zeros [8]. In this paper we have considered two values of probability of occurrence of $p_{i,j} = 0$: 5% and 10%. Additionally, for the calculation of the objective function it is necessary to calculate the due-date of each job j (d_j). In this case, literature guidelines presented in [27] were followed, where the due-dates are calculated according to the following formula for a job j: $d_j = \sum_{i \in I} p_{i,j} \cdot (1 + random \cdot 3)$, where *random* is uniformly distributed value between 0 and 1.

To evaluate the experimental results, we have used the Relative Percentage Deviation (RPD) to measure the performance of the algorithms. The RPD is obtained using the following formula:

$$RPD = \frac{S-B}{B} \cdot 100\% \quad (2)$$

Where S is the solution to be evaluated and B is the best known solution for that instance. For the assessment of the algorithms 30 runs where performed for each instance. Thus, we will report the average and standard deviation of the RPD. These values are computed for both algorithms, ssGA and SA. Then, the indicators are identified as $Ave.RPD^{ssGA}$ and $Dev.RPD^{ssGA}$, which represent the average values of RPD and its standard deviation for the ssGA algorithm, and, $Ave.RPD^{SA}$ and $Dev.RPD^{SA}$ in the case of SA, respectively. In order to compare NPFS and PFS solutions, the average relative improvement of the NPFS solution over the PFS solution, $Ave.NPFS$, is calculated. This improvement is measured with the following formula:

$$Ave.NPFS = \frac{sol.PFS - sol.NPFS}{sol.PFS} \cdot 100\% \quad (3)$$

Where *sol.PFS* represents the best PFS solution obtained by means of ssGA, and *sol.NPFS* represents the best solution obtained by means of SA for the same problem. $Ave.NPFS$ expresses the average value of that difference for the 30 runs. In turn, the standard deviation of these differences (between *sol.PFS* and *sol.NPFS*) was also computed, which is indicated as $Dev.NPFS$.

4.2 Experiments results

The values of *Ave.RPD* and *Dev.RPD* for the ssGA and SA algorithms are presented in Tables 1 and 2, respectively. Comparing both algorithms, it can be seen that they have similar performances, both in terms of the RPD average and standard deviation. In the case of RPD and problems with 5% skipping operations, the range of values for both algorithms goes from 4%, for problems with 20 machines and 80 jobs, up to around 40%, for problems with 10 machines and 40 jobs. In regard to the instances with 10% skipping operations, the range of values for both algorithms is around 6% for instances with 20 machines and 80 jobs. In the cases of 20 machines and 40 jobs, the RPDs differ between both algorithms, being 34.7% for ssGA and 39.4% for SA.

From the data in Tables 1 and 2 it can be suggested that, at least for the instances considered in this analysis, when the number of machines is closer to the number of jobs in absolute terms (in these cases, it would be 20 machines and 40 jobs), the RPD is maximum for both algorithms and both percentages of skipping operations. Thus, these instances are more difficult to solve for the algorithms. Another supporting argument of this inference is related to standard deviations. These are larger for instances of 20 machines and 40 jobs, those problems whose matrix of processing times tends to be more square when compared to the other problem sizes (15 machines and 40 jobs, and 20 machines and 80 jobs). However, a larger experimental work is required to draw a thorough conclusion regarding this aspect.

Table 3 presents the results of the solution comparison between the PFS and NPFS approaches. In Table 3 it can be seen that in the majority of cases NPFS solutions are better than PFS, as evidenced in the "*Improvement Freq.*" columns, since this percentage is larger than 96% for all the instances. In regard to the effect of the probability of skipping operations, when it is 10%, it is evident that NPFS is superior in all the cases except for the case of 20 machines and 40 works (in which NPFS is better in 98.7% of

the time). Regarding the improvement in terms of the objective function, on average NPFS is better than PFS, since all the values of the "*Ave.NPFS*" columns are positive. These improvements range from 0.5% for 20 machines and 80 jobs and 5% of skipping operations, to 2.8% for 20 jobs and 40 machines. When considering the instances with 10% of skipping operations, it is observed that this improvement increases, since instead of the 0.5% improvement in the problem of 20 machines and 80 jobs, it goes to 0.9% improvement. For 20 machines and 40 jobs, the improvement goes from 2.8% for 5% of skipping operations, to 3.97% for 10% of skipping operations. The standard deviations of NPFS improvements over PFS ("*Dev.NPFS*" column) also increases going from 5% to 10% of skipping operation.

Table 1. Average and Deviation RPD values for ssGA.

m	*n*	*Ave. RPD*^{ssGA}		*Dev. RPD*^{ssGA}	
		5%	10%	5%	10%
15	40	20.0%	15.5%	8.6%	9.5%
20	40	38.7%	34.7%	25.4%	20.0%
	80	4.3%	6.0%	2.3%	3.2%

Table 2. Average and Deviation RPD values for SA.

m	*n*	*Ave. RPD*^{SA}		*Dev. RPD*^{SA}	
		5%	10%	5%	10%
15	40	17.9%	17.3%	10.4%	10.0%
20	40	40.2%	39.4%	25.6%	22.9%
	80	4.6%	6.4%	2.4%	3.3%

Table 3. Solution improvement of NPFS approach over PFS approach.

m	*n*	*Ave.NPFS*		*Dev.NPFS*		*Improvement Freq.*	
		5%	10%	5%	10%	5%	10%
15	40	1.83%	3.53%	1.73%	2.20%	96.7%	100%
20	40	2.80%	3.97%	3.36%	3.74%	96.0%	98,7%
	80	0.50%	0.95%	0.43%	0.50%	99.3%	100%

5 Conclusions

This work addressed a scheduling problem in Flow shop systems that arises in Industry 4.0 manufacturing environments. This is the scheduling problem with skipping operations that takes into account the increase in personalization of products to meet the specific requirements of customers. To address this problem, this work proposes an innovative way to consider NPFS solutions to find efficient production schedules, seeking to minimize the total tardiness. Two meta-heuristic algorithms are presented that

allow to tackle realistic size instances, a steady state Genetic Algorithm (ssGA) and a Simulated Annealing algorithm (SA). Both algorithms were effective in addressing the instances considered in the experimental study. Specifically, the ssGA was used to optimize the PFS approach, and SA was used to optimize the NPFS. When comparing solutions, it was observed that NPFS tends to outperform PFS solutions in the vast majority of cases. Even when considering different proportions of skipping operations, it was observed that NPFS tends to increase its dominance over PFS when increasing the percentage of skipping operations.

To continue advancing in this line of research, it is proposed to approach problems that consider other types of objective functions, for example, objective functions of the regular type (e.g. makespan), as well as multi-objective problems. Additionally, another future research avenue would be to expand the experimentation by considering instances with larger percentages of skipping operations.

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Future research agenda to understanding the Sustainable Business Model in Industry 4.0

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Abstract. All over the world, Industry 4.0 (I4.0) and Sustainable Development (SD) have progressively gained the interest of scholars, politicians, and other parts of society. Besides beings two of the most debated topics of the last decades; they also have overlaps between their independent research fields. Some examples are reductions of environmental impacts and improvements in production technologies. This integration of technologies and sustainable advances within an industrial context can enable a set of important competitiveness forces, which results can reflect in business improvement. However, the link between I4.0, SD, and business still needs a broader understanding. Basing on this perspective, this paper proposes a systematic literature review (2015–2020) to identify the current state of research on the subject by mapping and summarising existing research efforts, as well as identifying research agendas, gaps, and opportunities for more development. Results point to that there are fourteen research opportunities, showing the potential of Industry 4.0 as an enabler of sustainable business models that changes the responsibilities of companies.

Keywords: Industry 4.0, 4th Industrial Revolution, Sustainability, Business Model, Systematic Literature Review.

1 Introduction

The overlap between Sustainable Development (SD) or Sustainability and Industry 4.0 (I4.0) or also called the fourth industrial revolution has been one of the most important industrial debates in recent years [1,2,3,4,5,6,7,8,9]. But, although the I4.0 revolution can be described as a facilitator for sustainable development, this union remains underdeveloped in many aspects [3,5,6,10,11,12,13]. One of these aspects is about Sustainable Business Models (SBM) into the I4.0 revolution [1,2,3,4,14].

The new era of smart production can provide companies with a more aggressive attitude to embrace opportunities. As pointed by Porter and Heppelmann [14], the

changing nature of products will force many companies questioning what business they doing because new products raise a new set of strategic choices related to how value is created and captured, in other words, it redefines the value chains and business models [1,6,8,10, 14,15].

Based on this observation, the study present here was structured into three questions (Q). The set of questions increase understanding about how two of the most debated topics of the last decades are being discussed now to support future research agenda (Q1); mapping the field (Q2), and, finally, showing the chronological evolution (Q3). The questions are as follows: (1) What are the opportunities for future research agenda?; (2) Where this topic is being investigated?; (3) What is the current status of this research field?.

2 Conceptions description

The study is based on three main concepts, I4.0, SD, and SBM. In this section, these concepts are presented.

2.1 The connection between Industry 4.0 and Sustainability

Sustainability does not have a unique definition [16]. Due to this, concrete implementation is considered difficult because there is a high degree of complexity regarding the depth and specifications of the fields of action [3,16]. However, the most common definition cited was presented by the Brundtland Report, which describes sustainable development as "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" [17]. Besides this definition, another highly referenced concept is the Triple-Bottom-Line (TBL), whose objective is to operationalize sustainability through the balance between economic profitability, respect for the environment, and social responsibility [18]. The common meaning among these different approaches is the general scope to support the increase of the companies' competitive capacity [19] and improve the use of their resource productivity [20].

Likewise, I4.0 is also a paradigm whose unique definition is not possible due to its wide range of approaches [2,21,22]. Most definitions consider I4.0 as a digital technological advance to make industrial production systems more intelligent, connected, and capable of decentralizing production [2]. Some practical examples of new technologies of revolution 4.0 used in the industry are: big data and analytics, Internet of Things (Internet of Things (IoT)), augmented and virtual reality, simulation, robots and autonomous vehicles, additive manufacturing, cloud, cybersecurity, among others.

According to Kuik and Diong [23], I4.0 refers to extracting real-time data and developing new and innovative information systems (IS) through the use of computer and/or sensing devices as well as information communication tools. In the same way, Piccarozzi et al. [22] state that I4.0 is based on the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customized production.

Many publications on I4.0 and sustainability are dedicated to the economic and environmental dimensions [3,21]. Although I4.0 also has enormous potential for the social dimension [6]. In the economic dimension, most of the literary contributions of I.40 to sustainability relate to the proposal of new technologies to reduce manufacturing costs through systems integration [6]. In the environmental dimension, most of the literary contributions of I.40 to sustainability are related to improving the standard of living of the society and increasing the quality of production without causing damage to the environment [6]. In the social dimension, most of the literary contributions of I.40 to sustainability are related to predicting better conditions and beneficial opportunities for workers [11].

The predictive use of production data provide by I4.0 toward more sustainable industrial value creation will change the ability to make planning production for competition between non-sustainable and sustainable products [6,8,23,24]. Therefore, is also highlights the impact of this union in business management models and firms' main components and the importance of more studies with this domain [22].

2.2 Sustainable Business Model (SBM)

A new business mindset can generate many advantages and challenges. When sustainability is added to the core of the business model concept, it can systematically change the purpose of the company [25]. In this regard, SBM offers opportunities for companies to rethink their process of value creation, product production, pro-active multi-stakeholder management, and long-term perspective [1,7,26].

At the same time, SBM can be limited by the introduction of incremental or radical innovations [1]. According to Inigo et al. [27], evolutionary approaches, based on incremental sustainability innovations, adjust the creation of value to respond gradually to market needs. On the other hand, radical innovations introducing new value propositions to address a new sustainability issue. This way can result in the creation of an unprecedented market segment.

Among diverse SBM definitions, Schaltegger et al. [28] argue that a business model for sustainability "describe, analyze, manage, and communicate (i) a company's sustainable value proposition to its customers, and all other stakeholders, (ii) how it creates and delivers this value, (iii) and how it captures economic value while maintaining or regenerating natural, social, and economic capital beyond its organizational boundaries". On the other side, it is possible to find SBM definitions based on Brundtland Report as in Garetti and Taisch [29] that describes SBM as the preservation of the environment, while continuing to improve the quality of human life. Dyllick and Hockerts [30] view SBM as the meet the needs of a firm's direct and indirect stakeholders without compromising its ability to meet the needs of the future. Similarly, Bansal and DesJardine [31] argue that SBM is the ability of firms to respond to their short-term financial needs without compromising their (or others') ability to meet their future needs.

3 Review methodology

To better identify the relationship between I4.0, SD, and SBM, a Systematic Literature Review (SLR) was implemented according to Tranfield et al. [32] procedures. A literature review is essential to strengthening the field of study [32]. As scientific inquiries, the SLR should be a transparent, valid, reliable, and replicable method for identifying, describing, evaluating, and synthesizing evidence related to a specific topic [32]. The SLR rigors ensure that the result found has scientific validity since it describing the information with the least possible distortion and errors; also, because it has the legitimacy to improve knowledge development and make decisions [33].

To secure the validity and transparent rigors of SLR, specific databases were selected: Scopus and Web of Science. These databases were used because contains a significant number of internationally renowned publications, like Springer, Elsevier, Emerald, and Taylor and Francis. The review process considered only formal literature that was: (i) written full-texts in English, (ii) published between May 2015 and May 2020; (iii) peer-review published papers. Then, a structured keyword search was conducted executed through a pairwise query, focusing on titles, abstracts, and keywords.

Table 1. Search results

	Keyword pairwise query	Scopus	Web of Science
1	TITLE-ABS-KEY ((sustainability AND business model AND industry 4.0))	8	4
2	TITLE-ABS-KEY ((sustainability AND new business model AND industry 4.0))	4	2
3	TITLE-ABS-KEY ((sustainability AND organization improvement AND industry 4.0))	1	1
4	TITLE-ABS-KEY ((sustainability AND maturity model AND industry 4.0))	1	0
5	TITLE-ABS-KEY ((sustainability AND maturity evaluation AND industry 4.0))	0	0
6	TITLE-ABS-KEY ((sustainability AND dynamic capability AND industry 4.0))	2	0
7	TITLE-ABS-KEY ((sustainability AND strateg* AND industry 4.0))	17	3
8	TITLE-ABS-KEY ((sustainability AND competitiveness AND industry 4.0))	7	1
9	TITLE-ABS-KEY ((sustainability AND competition AND industry 4.0))	9	2
10	TITLE-ABS-KEY ((sustainability AND value creation AND industry 4.0))	8	4
11	TITLE-ABS-KEY ((sustainability AND strategic planning AND industry 4.0))	0	0
12	TITLE-ABS-KEY ((sustainability AND product AND development AND process AND industry 4.0))	12	3

13	TITLE-ABS-KEY ((sustainability AND product AND development AND industry 4.0))	20	3
14	TITLE-ABS-KEY ((sustainability AND product AND industry 4.0))	33	7
15	TITLE-ABS-KEY ((sustainability AND continuous improvement AND development AND industry 4.0))	1	1
	Total in each database	123	31
	Final result	154	

In each database, 15 different search strings were used. Table 1 reports the search strings and the resulting number of papers in each database. The search found 154 papers from both databases. To refine the results further, duplicate papers were exclusion. The total numbers of articles dropped to 36 papers after reading the abstract according to the review purpose for the final review.

4 Results and analysis

This section made a descriptive analysis of the whole sample. Even at a general level, the database allowed extrapolation of interesting information. This information will be presented according to the order of the questions. Started by (Q1): What are the opportunities for future research agenda?. Not all authors present directions for future research. However, fourteen opportunities for further investigation were identified (see Table 2).

Table 2. Future research opportunities

N	%	Future research directions
1º	16,70%	Apply the study in large-scale
2º	16,70%	Analyze the different functions of the company in interaction with I4.0
3º	10,60%	TBL dimensions in the context of the I4.0
4º	9,10%	The impact of I4.0 on supply chain network design
5º	9,10%	The impact of I4.0 on managing customer channels
6º	8%	Employee quality
7º	6%	How Industry 4.0 will change the competition
8º	6%	How incorporating the I 4.0 into theory about sustainable value propositions
9º	6%	Qualitative research
10º	4,55%	Cost-benefit analysis of Industry 4.0 solutions
11º	3,03%	Policy-making efforts to I4.0
12º	1,52%	Transformations in the identity of a manufacturing company
13º	1,52%	Risk assessment to I4.0 implementation
14º	1,52%	Ensure data security

Two of these were the most mentioned: apply the studies in large-scale and analyze the different functions of the company in interaction with I4.0. The first opportunities are regard to test the empirical observations found in each paper in a large-scale study of

companies since very small to bigger ones; in the context within and across industries; applied to any business function; into new customized segments; diversified markets; between different cultures and nations; and different methodologies [21,34,35,36,37,38,39,40,41,42,43,44]. In more, could be investigated its influence on other business models types, such as product-focused and result-focused ones [37,38].

Analyze the different functions of the company in interaction with I4.0 is an option for future research to observe the shift industry boundaries and theories of the firm within a manufacturing context [1,7,34,35,45,46]. More investigations are needed to analyze how can the currently highly production-oriented developments and the data they generate be included in the entire corporate information and decision-making processes [1,46]. Additionally, future research projects should take into consideration other key variables and outcome to give a broader view on it specific characteristics and requirements that influence the implementation of I4.0, e.g., top management support, metrics of performance, environmental uncertainty, digital servitization, new technologies, absorptive capacity, and so on [6,21,26,37,38,43,45].

Investigations on TBL dimensions in the context of the I4.0 shows that there is still a lack of investigations about the interplaying and conflictive relationships between dimensions [1,6,7,13,26,37]. Furthermore, current research emphasizes the need for more studies on the social impacts of I4.0 [3,21,26,47].

Possible contributions to the impact of I4.0 on supply chain network design can analyze how it facilitates reverse logistics to reduce production waste, overproduction, and energy consumption; focusing on production planning, structure, and control of product recycling [4,6,42]. Additionally, the resource-sharing aspect of sustainable business models [49].

Future research about the impact of I4.0 on managing customer channels should try to describe it in the creation of sustainable awareness of customers, customer loyalty, and satisfaction for sustainable I4.0 products/services [4,7,45].

More detailed investigations should observed work quality between humans and machines regarding which job profiles emerge and which diminish because of the I4.0 [13,21,49]. This opportunity for future research is linked to social dimension issues. But, here further research is needed on the issue of accidents involving hazardous chemicals, new tools, and techniques by developing technologies I4.0; and, professional training [6,42].

A research agenda is also needed to explain how I4.0 will change the competition, especially, between non-sustainable and sustainable products [4]. Is also necessary to verify how it improves the competitiveness of the company over time, i.e., in the long-term [47]. As well as the role of dynamic capabilities in resource reconfiguration and processes it changes require [45]. Moreover, future research should examine how I4.0 transforms bargaining power in different sections of manufacturers [45].

How incorporating the I4.0 into an organizational theory about shape new sustainable value propositions is a gap to further studies close [4,48]. As well how can organizations integrate, analyze, and exploit data to generate sustainable value-propositions [48]. Novel insights are needed to explore how manufacturers shift their value creation and capture from product-centric to service-centric, and further to data-centric [1,21,45].

Quantitative research is another future possibility to check results presented in articles [34,36,50], more specific to measure social and ecological impacts [3]. Valuable contributions are needed regarding the cost-benefit analysis of Industry 4.0 solutions to supported sustainable products [4,45]. In this cost, the transaction should be analyzed downstream and upstream interactions [45].

Literature has lacked studies, since the debate on this theme is recent, on policy-making efforts to foster the development of I4.0 by national and local governments. Potential studies can explore the regulation of political, financial, and fiscal aspects, as well as the provision of infrastructures, services, knowledge, and a skilled workforce [26,51]. Moreover, based on the scarcity of results of the SLR, there is a need to urgently investigate how I4.0 transforms the identity of a manufacturing company [45]. In the same line, must be better understood the risk assessment to I4.0 implementation, depending on short, medium, and long-term management, different corporate and environmental contexts [50]. Finally, although ensure data security is a point commonly debated in studies about I4.0, few articles in the sample of this SLR highlighted the need to further investigations of it by a sustainable business model perspective; how it would be developed, and what companies think about it [26,34,46].

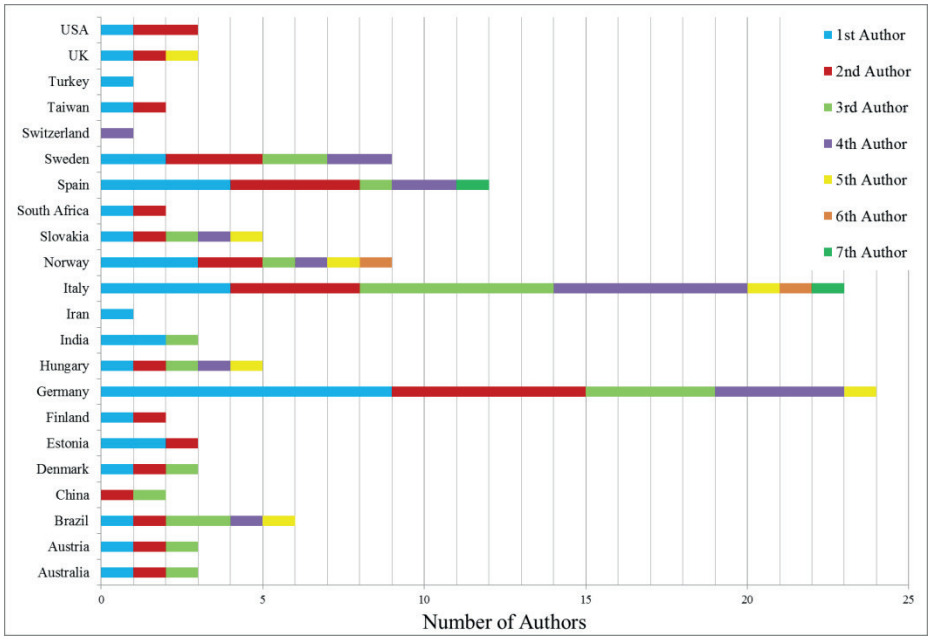

Fig. 1. Authors' affiliations countries.

Data to (Q2) Where this topic is being investigated?, considering the authors' affiliations, reveals that there is a strong predominance of German (19,2%) and Italian (18,4%) authors, as shown in Figure 1. The next predominance countries perceptual contributions are Spain (9,6%), Sweden (7,2 %), and Norway (7,2 %). The other 17 countries' contributions accounted for about 38,4% of the total number of works

published. This shows that the major research contributions are coming from countries with few authors. This means that, despite the dominance of German and Italian authors, this field of research is of interest to several countries.

The detail of figure 1 also showed that the greatest number of first authors is from Germany, Italy, and Spain. This result is equal to the second authors. Most of the third and fourth authors are form Italy and Germany. Fifth authors predominate with the diversity of countries: Slovakia, Norway, United Kingdom (UK), Italy, Hungary, Germany, and Brazil. Sixth and seventh authors are from Norway and Italy, Spain, and Italy, respectively.

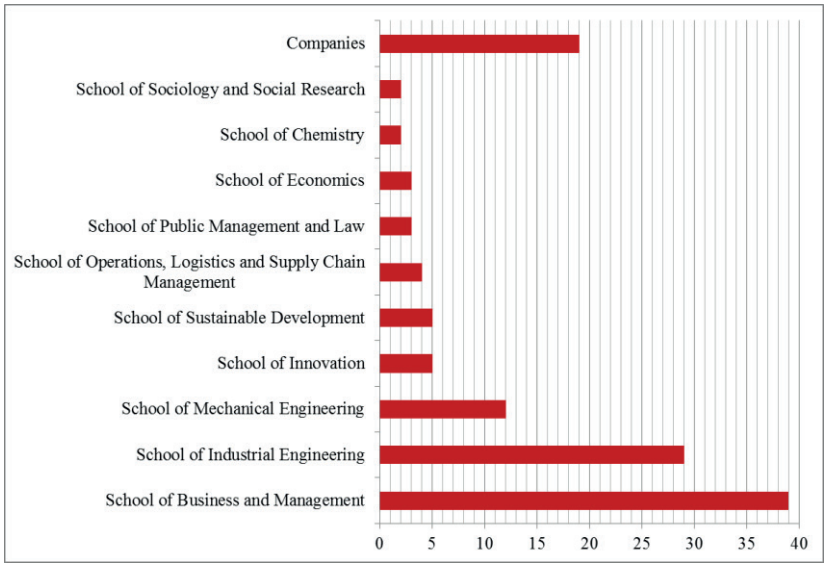

Fig. 2. Authors' affiliations school.

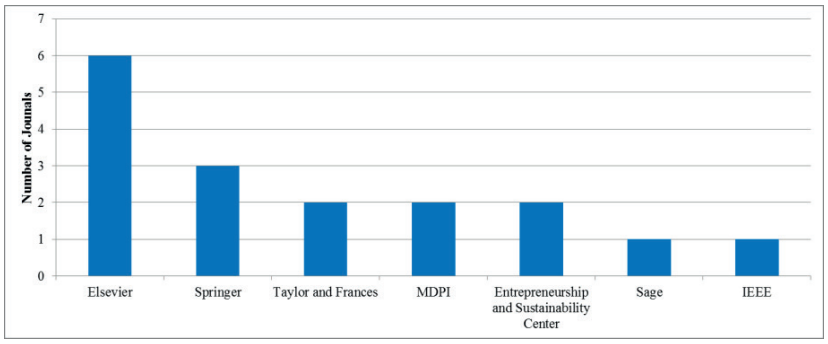

Fig. 3. Publisher list.

According to the authors' affiliations, figure 2 shows from what school each author is. Most of them are researchers in business and management (31,7%), then engineering (23,5%) and mechanical engineering (9,75). Authors' affiliations from companies

represent 15,44% in the sample. Most of them work in automotive companies, production systems advisory, financial, and innovation consultancies.

Going into contributions by publishers, figure 3 reveals that Elsevier has the highest number of scientific journal titles, with six journals, followed by Springer with three scientific journals title. However, the journal with the highest contribution (number of papers published) is Sustainability from MDPI Publisher (see Fig. 4).

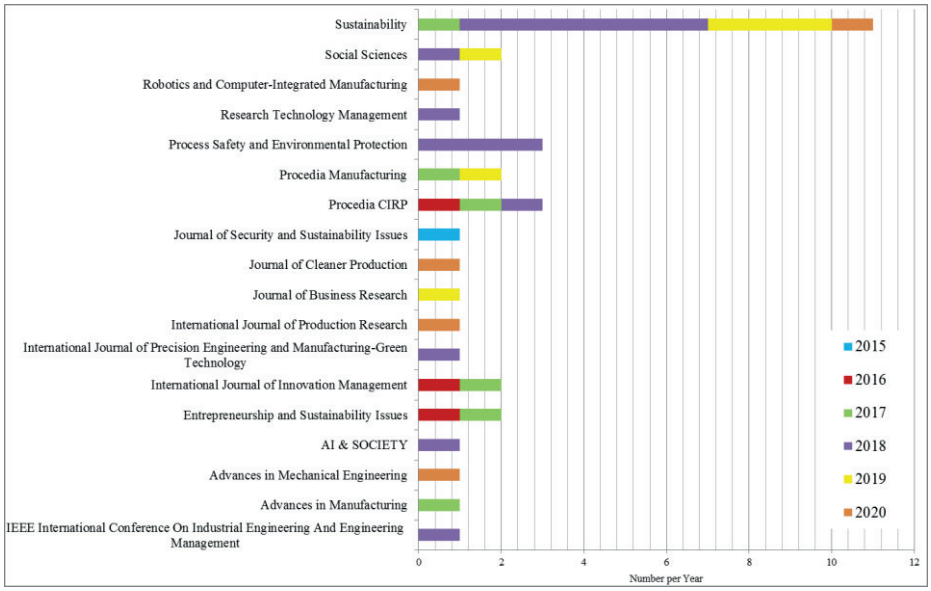

Fig. 4. Journal titles list.

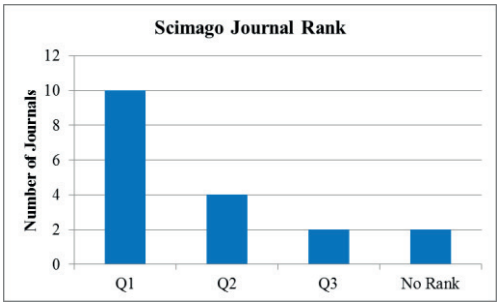

Fig. 5. Journal rankings by Scimago.

Regarding the quality of these scientific journals, their classification in Scimago was verified to analyze their impact factors. As shown in figure 5, most journals have a great impact factor, being classified in Q1 (the best rating). Looking at how many contributions each journal had, the result pointed out that most articles are from journals with a Q2 classification. Besides, it was possible to identify the main topics of each journal according to the description of Scimago (see Fig. 6). The close link between business, I4.0, and engineering proved to be relevant because the most cited subjects were

engineering and business, management and accounting; following the three dimensions of the TBL: environmental science, finance, and social sciences. In particular, this emerging link can also be verified by looking at journal titles. One-third of the entire sample deals specifically with the topic of sustainability, but not the other two (Sustainability, Entrepreneurship and Sustainability Issues, Journal of Security and Sustainability Issues, Process Safety and Environmental Protection, Journal of Cleaner Production, International Journal of Precision Engineering and Manufacturing – Green Technology).

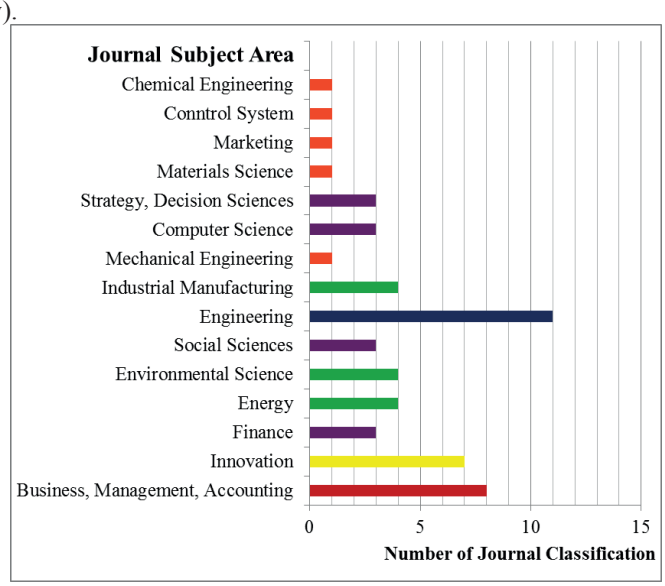

Fig. 6. Journal Subject Area list.

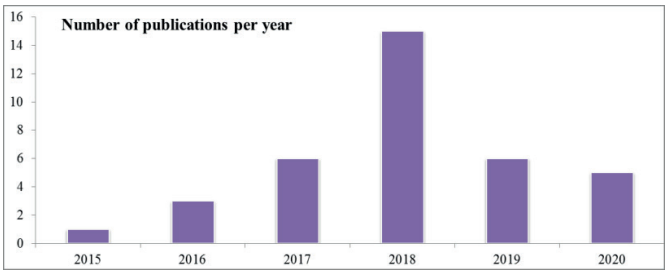

Fig. 7. Chronology of article publications.

The chronologic data to answer Q(3) What is the current status of this research field?. revels that there was an upward trend observed from the year 2015 to 2018 (see fig. 7). However, the number of papers published from 2019 onward has decreased drastically. It is observed that 69,44% of total papers were published in the year 2015–2018. In contrast, 2019 revealed little attention devoted to these topics by the authors. Papers' date to 2020 was published only in April and March. This outcome highlights the need for more studies covering this important link between business model, sustainability, and I4.0.

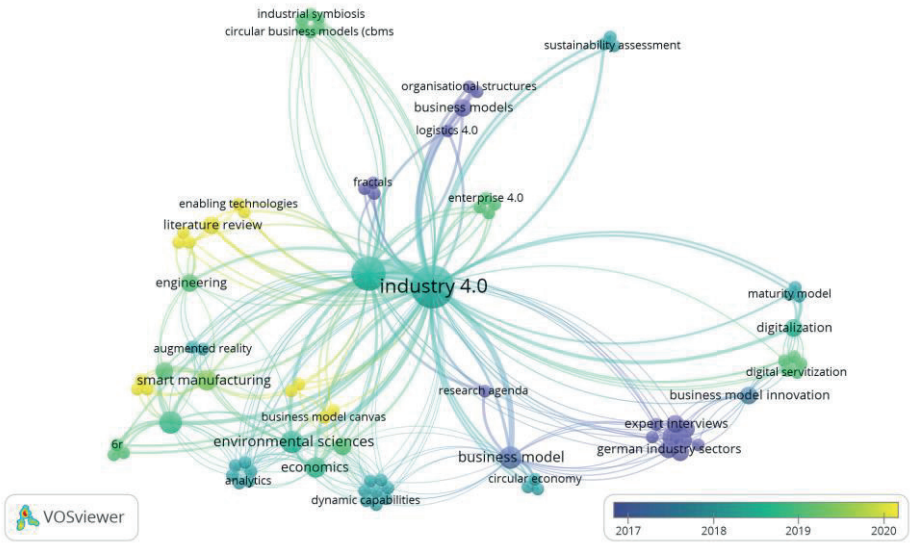

Fig. 8. Chronology of article publications by keywords.

Another way to observe how is the theme currently is looking at keywords statistics (see Fig. 8). Here, were extracted the most commonly used keywords in all selected papers using the VOSviewer tool [52]. The most frequent keywords used until 2017 were: business model, research agenda, expert interviews, German industry sectors, logistics 4.0, and organizational structures. The most frequently keywords used in 2020 were business model canvas, smart manufacturing, literature review, and enabling technologies.

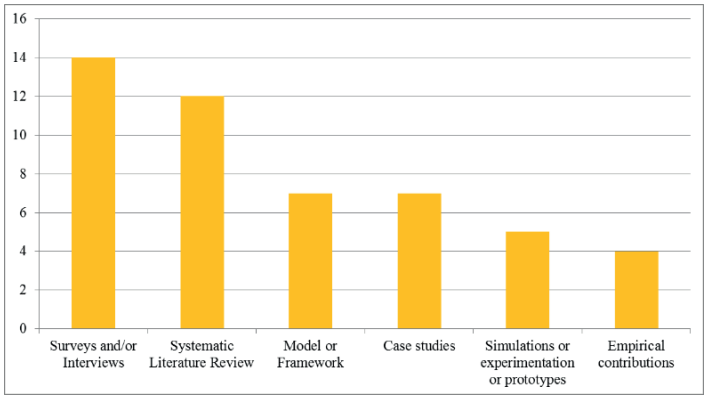

Fig. 9. Chronology of article publications by methodologies.

Finally, fig. 9 shows the distribution of the selected 36 papers by methodology. The sample is mostly made of surveys and/or interviews (28,5%). Then, systematic literature review (24,4%), model or framework (14,2%), case studies (14,2%), simulations

or experimentation or prototypes (10,2%), and empirical contributions (8,16%). One important observation about papers' type of research was the change of type year by year. In the initial years 2015 until 2017, most of the articles were surveys or interviews, case studies, and simulations, experimentation, or prototypes. From 2018 until 2020, the main papers' type of research was a systematic literature review and model or framework. Based on this, it can be said that this recent topic was initially studied from a practical and expert point of view, while in more recent years conceptual and theoretical research has become more frequent.

5 Conclusion

This study aimed to investigate, through a multidisciplinary lens, the current state of research on the theme I4.0, SD, and SBM performing an SLR. 36 articles were analyzed for this purpose. Based on the limited number of articles analyzed and the initial proposal, this study was not intended to use statistical analysis or to provide a more in-depth analysis of specific topics. However, this review was successful in demonstrating the potential of introducing I4.0 into SBM. We conclude that I4.0 is an enabler for sustainable business models that changes the responsibilities of companies, making them responsible for their entire consumption system, and not only for the production and sale of consumable goods. This crossing of borders introduced a competitive advantage of high technology that initially approached a vision of technocentric evolution for a holistic view. Nevertheless, our results have some limitations due to its qualitative nature. Selected keywords and databases may be one of the limitations of this article, as there may be articles relevant to the scope of the study outside these criteria that were not considered. Finally, the result highlighted the need for further research. A research agenda for the development of sustainable business models were presented in the results section. Future work can also extend the analysis made by this SLR and focus on how the union of the observed themes reflects in the science of business and management, such as company theory, strategic planning, and so on.

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Universities Best Practices in Open Innovation and R&D

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Abstract. The growing significance of innovation ecosystems and the need for collaboration projects, as well as Open Innovation (OI) practices, has been shaping the way as universities produce Research and Development (R&D), impacting Product Lifecycles Management (PLM) directly. The collaboration between different actors enrolled in the development of new products and services is a growing trend, indicating more challenging innovation processes. It is possible to find in literature and empirical knowledge that R&D and OI, even separately, can be complicated and more extensive than expected. Innovation process complexity can be more demanding, especially when its crucial to consider the context of new technologies, sustainable and user-centric and other approaches and more recently, new crises such as pandemics restrictions. This paper aims to realise a literature review in qualified databases, to find the best practices that universities have been carrying out in recent years in Open Innovation concerning Research and Development. Primarily, the goal of this study is to find the literature contributions in OI and R&D in universities and its respective characteristics and further, try to obtain information about the elements that can be related to as development methods, product lifecycles, results and particularly R&D impact. The central purpose of this paper was to find relevant information for innovation management in universities and industries, and through the data gathered from the literature, to generate inputs to foster future R&D and OI research projects, closing the gap between university and industry and promoting greater outcomes.

Keywords: Open Innovation, Research and Development, Higher Education, Universities Best Practices, Product Lifecycles Management.

1 Introduction

1.1 Context

The efforts to obtain original sources of innovation are increasing daily in organizations of every industry. As the main point of competitivity or for different purposes, innovation has been the theme in the priorities agendas of every company which aims to survive. Some concepts, theories, practices of innovation have been raised in several approaches, but it is not more acceptable that one only one company can answer all facets demanded by innovation. In response to this urgency of contemplating different stakeholders or actors with their needs and expectations, raised the Open Innovation (OI) concept [1]. Open innovation is a process which combines internal and external ideas

in overture with the market to develop new ideas and technologies – such as systems or architectures. The authors of the concept understand that Open Innovation changes Research & Development perspective, treating it as an open system since the flows of ideas are able to come inside and outside the organization able to be applied or commercialized inside or outside this organization. [2] Since then, OI applications have been evolving according to the context, always in order to obtain broader and more successful results for innovation.

It can be observed that to deal with the evolution of research, development and innovation, the universities have been changing their approach. To foster Research and Development in openness with other organisations and to be market-oriented, the different initiatives have been emerging, giving an expanded vision for the so-called university-industry collaboration.

For this reason, universities have been engaging or creating their own innovation ecosystems have several approaches and programs to seed entrepreneurship, incubation and acceleration programs, technology transfer offices, which means that articles, patents, software, products, start-ups and more innovation outcomes are presented in different stages of Product Lifecycle requiring new approaches for its management.

The authors of this paper have been studying the purpose of the university in the face of the challenges of sustainability and innovation and its role as the protagonist of change management troughs its outputs: high-quality professional education, knowledge provider, science, research and development and more [3]. It is from this context that the present work aims to search in the literature, best practices of universities have been carrying out in recent years connecting the themes of Open Innovation concerning Research and Development and Product Lifecycle Management.

1.2 Background

The purpose of open innovation is to reorganise innovation processes leading flows of knowledge beyond organisational boundaries [4], which means that more opened sources of external knowledge have been proven to facilitate better outputs for innovation [4]. It is based in this concept that all sort of enterprises has been working close to universities, government, suppliers, customers to gather brand-new and unexpected knowledge to develop more innovative products, services and processes. In other words, the OI practices can be extended to innovation management research and practice and with its interactions with business ecosystems [5].

The model of the Triple Helix proposes interactions between university-industry-government as innovation pillar. [5] The interactions between these three actors are organised in the Triple Helix model in order to understand the role and contributions of each institution for innovation as well as the variables and quality of these relations as institutional and functional arrangements and its ability to foster innovation outcomes. [6]

Additionally, it is necessary to understand the concept of Product Lifecycle Management (PLM), which summarily means the activity where organisations manage their products considering all the stages of the complete lifecycle: since the idea conception, including production, distribution and including product post-use until the disposal. [7]

Three macro-phases are the pillar of the Product Lifecycle: a) beginning of life (BOL) which contemplates phases such as product planning, design and production and distribution; c) Middle-of-life (MOL) which includes phases such as utilisation, service and maintenance and finally; c) End-of-life (EOL) that contains the phases or reverse logistics, disposal, reuse, recycling. [8]

Considering the context of Fourth Industrial Revolution, sustainability challenges, there is a large field of opportunities to apply Research & Development in different stages of Product Lifecycle and Open Innovation seems to be a useful and effective approach to support the innovation specially the innovation developed by universities, which are the main interest of this study.

Universities play an essential action in the OI contribution since they are a significant knowledge provider for Research and Development (R&D) [10]. The practices of OI now becoming more present in innovation activities in university-industry-government, which has been shaping the new approaches as universities produce Research and Development (R&D) impacting Product Lifecycles Management (PLM) directly.

Thriving entrepreneurial ecosystems count with an excellent capacity to transform inventions into innovations and in to commercialise knowledge. For this reason, universities are considered as key actors within the entrepreneurial ecosystems to perform knowledge commercialisation through academic spin-offs and technological development [10]. The university function is perceived as an essential motor of product development – independently of which stage of the lifecycle it is, and always supported by research and development.

Furthermore, there are significant contribution for product lifecycle in stages such as: stakeholder engagement, proposition of new ideas; validation and evaluation of product concepts; creative approaches and product launch [11]. Moreover, PLM moves beyond engineering's incorporating manufacturing and marketing, and it is to become product-centric, crossing organisational boundaries, observing its supply chain and contemplating all the phases of the product's life: create, build, use and disposal [12, 13].

2 Method

2.1 Literature Review

2.1.1 Data search

This paper aims to conduct a structured literature review [14, 15, 28, 29], in qualified databases, to find the best practices that universities have been carrying out in recent years in Open Innovation concerning Research and Development and its best practices and the relations of Open Innovation.

The search for articles to fulfil the proposed goal, included the terms: Open Innovation (OI) and Research and Development (R&D). Additionally, a complimentary search was done to obtain extra data regarded to Open Innovation (OI) and Product Lifecycle (PLM). In both cases, the searches were combined with the word University as the exposed following (Fig. 1).

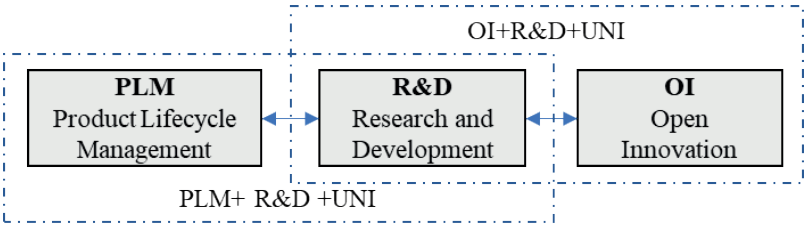

Fig. 1. Keywords relation.

Scopus and Web of Science were the databases chosen for the search; both are internationally known by the widely quality of content, large metadata availability and usability to conduct the queries. The combination of keywords for this universe search is illustrated below (Fig. 2). Additionally, as the first criterion of inclusion, the search included exclusively articles published in English and 2009-2020 as time coverage.

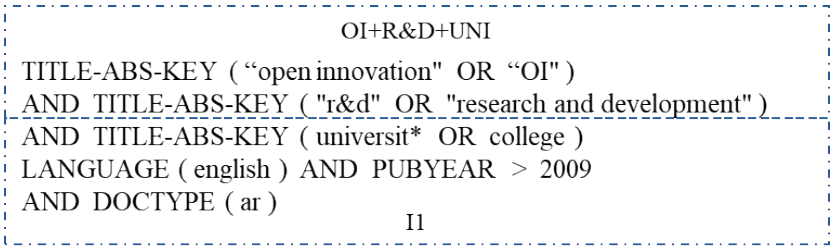

Fig. 2. Query example.

The literature review contemplated eight steps, separated in three groups of activities: 1) Databases search of the keywords combined, as the example in figure 2; 2) Database organisation: removal of duplicated articles and exclusion of articles that are not related to the scope of the study. 3) Inclusion criteria: quality, language and reading of articles metadata.

The queries keyword in databases search resulted in 542 articles, with the removal of duplicated files and the out of scope, the total base contemplated 488 articles to be read. Only the papers published in the first quartile (Q1) according to *Scimago Journal Ranking* – 2018 were selected to the next phase, resulting in 186 sources. Finally, the articles selected to this work are which presented all the studied words (Open Innovation, Research and Development, Product Lifecycle Management and University) in all fields (title, keywords, abstract). After that, all the metadata of the articles were read, resulting in 12 final articles selected to full content analysis.

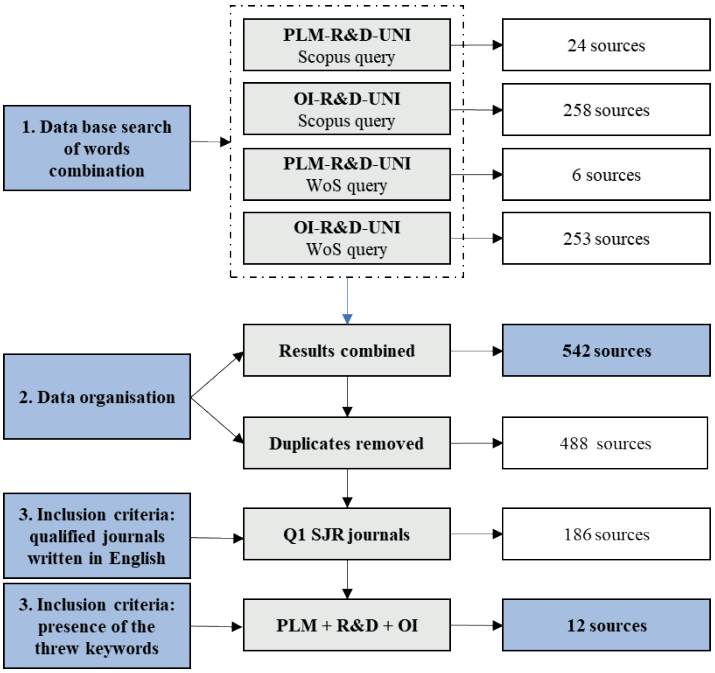

Fig. 3. Literature review steps.

2.2. Content analysis

The content analysis of the articles was conduct in two steps. Firstly, the authors analysed the general contributions of each paper, and secondly, the specific practices or contributions of the university regarding OI, R&D and PLM were interpreted. Table 1 presents the contributions, limitations and applications of each article. The works are presented by year of publication, in order to facilitate the theme's evolution through a timeline.

Table 1. Literature review findings.

Author(s)	Contributions	Limitations	Applications
Ebener, Liemiester, Krcmar (2009) [16]	Crowdsourcing for open innovation by multiple actors sustained by a system.	Gaps of concepts, tools and methods to support the innovation process.	Challenges and organisation structures for product development innovation.
Spithoven, Frantzen & Clarysse (2010) [17]	The impact of intensity of research on the innovative product to increases revenue.	Belgium contexts, self-reported data, quantitative analysis and few qualitative reflections.	Alignment for R&D expectations in short-term and long-term for managers.
Petroni, Venturini & Verbano (2012) [18]	How the OI has changed the organizational structures of R&D and the managing methods.	Four companies with very different profiles.	Best people management for open innovation in universities and companies, including roles beyond research.

Author(s)	Contributions	Limitations	Applications
López *et al.* (2014) [19]	Profiles of companies which collaborate with universities to R&D and country influence.	European countries and focus on small or medium enterprises.	Innovation actions to foster to non-technologies companies.
Bianchi *et al.* (2014) [20]	The benefits of the integration OI and R&D to PLM, focusing in internal and external paths.	Spanish context, solely manufactory companies and unappropriated dataset.	Inputs for successful new product development and licensing for tech companies.
Gesing *et al.* (2015) [21]	How the open innovation is impacted by governance models, collaboration partners, intern R&D to product development.	German context.	Insights about the level of formality and open innovation – R&D processes.
Oguguo, *et al.* (2015) [22]	The institutional context and the effect of national policies to foster innovation and R&D.	Firms benefited by 7TH Framework Program for Research and Technological Development.	Public policies advocacy.
Bianchi *et al.* (2016) [23]	OI and R&D to foster technological development.	Spanish context; Time scope (1999-2007). Quantitative approach lack of qualitative. Aggregation bias.	Insights about external technological.
Rubera, Chandrasekaran & Ordanini (2016) [24]	Open innovation applied to PLM: impact in product innovation and firm performance.	Focused on inbound open innovation.	OI applied for product lifecycle.
Naqshbandi (2016) [26]	The importance of management for effective open innovation results.	Study of management influences in a general approach, without specificities.	The function of management to across the boundaries in all OI actors.
Greco, Locatelli and Lisi (2017) [26]	Collection of pieces of evidence and factors which motivates companies to innovate.	Energy sector and British context.	The purpose of academia to support OI and the need for policies.
Triguero & Fernandez (2018) [27]	Geographic influences on Open Innovation, R&D and the actors' interactions related to product development.	SLR time scope (2003-2013); Spanish context.	Fostering regional ecosystem by technology domain.

The last ten year has shown the contribution of the university for open innovation. Even the search was conducted under some specific and combined terms, the study found the following contributions. Most of the articles have focus in the of Open Innovation for university-industry-government, but with general approaches privileging themes such as innovation management, internal organization and culture, and approaches [25, 21], companies' profiles and motivations [26], public policies [22], and methods for generation of innovation [16], There were some essays about firms' size; innovation programs appear more frequently than the university profiles.

Under the analysis of Research and Development as the central theme; the object of the study of the articles are mostly in concentered in subjects related to the impact [23],

intensity [17], revenue, structures and management for innovation in R&D [18]. Also, there are two studies which consider regional factors as influencers of innovation outcomes [17, 27].

Finally, by the perspective of Product Lifecycle Management, just two works presented a clear connection with the other studied themes. One study highlights the benefits of the integration of OI and R&D to PLM, including internal and external overviews [20]. Moreover, the second study that observes how OI applied to PLM impacts product innovation and firm [24].

As limitations, most of the article concentrates in regional contexts of countries or continents. Commonly, the approaches are qualitative or quantitative, and the authors agree that for each case, there is a complementary analysis missing to advance the studies. Also, there is not possible to find patterns of firm's profiles or uniform universities actions, firstly because of the nature of the innovation activity and secondly because it was not the scope of this study.

All the articles generated insights for future applications. These data are organized into two categories. The first category contemplates different approaches to foster innovation in different levels: inside the companies [16, 17], and universities [26], regional initiatives [19, 27], public policies [22]. The second category presented articles related of many interfaces of management for innovation: people management [25] [18], culture management [21] external scenarios, [23]. Relevant considerations of methods to work with innovation such as PLM applied to OI [21, 24].

To find the best practices of universities, regarded to open innovation, research and development and product lifecycle, the second part of content analysis evaluated the articles, in the same sequence presented before. This second part aims to identify how the studies about OI, R&D and PLM considers the importance and interactions with universities as presented in Table 2.

Table 2. Universities best practices.

Author(s)	Universities best practices
Ebener, Liemiester & Krcmar (2009) [16].	• Interface between company – universities – educational institutions. • Challenges of open innovation including all different actor to generate innovation for products and software development.
Spithoven, Frantzen & Clarysse (2010) [17].	• Universities are required to perform complex research. • Interorganisational collaboration with universities produces positive impacts in R&D. • Efficiency and opened R&D processes deliver successful innovation products and revenue.
Petroni, Venturini & Verbano (2012) [18].	• Growing number of contracts between enterprises and universities. • The interest of researchers in collaboration with highly specialised research firms. • Decentralisation of R&D structures allowing more and specialised collaboration with universities. • Development of R&D centres/laboratories inside companies to train universities students to be hired by this firms.
López *et al.* (2014) [19].	• Innovative firms and high-tech firms tend to be more opened to collaborations with universities. • Country factors may affect the collaborations university-industry.

Author(s)	Universities best practices
	• Non high-tech firms have interest in collaboration focusing in organisational and commercial innovation.
Bianchi *et al.* (2014) [20].	• Collaborations between firms and external organisations, such as universities and other actors, can result in better results in transforming technological resources in new products for different industries.
Gesing *et al.* (2015) [21].	• Partnerships with universities provides access to unique technological knowledge. • Technological breakthroughs and long-term commercial opportunities origined by applied and basic research. • Universities face few opportunities to commercialise intellectual property. • Contractual and formal governance tend to be more effective in science-focused collaboration than informal.
Oguguo, Bodas & Genet. Al (2015) [22].	• Evaluation of risks of cost, schedule, knowledge leakage in collaboration university-industry. • University as open knowledge provider. • Co-publication authored by firm-industry benefits and risks.
Bianchi *et al.* (2016) [23].	• Outsourcing of R&D from universities as knowledge and technology acquisition.
Rubera, Chandrasekaran & Ordanini (2016) [24].	• Universities as a source (between other sources) of Open innovation to development and commercialisation.
Naqshbandi (2016) [25].	• University-industry ties for OI may occur by management interactions. • Universities as knowledge and resources providers and influencers of OI.
Greco, Locatelli and Lisi (2017) [26].	• Universities as main influencers of OI to energy innovation. • Development of technologies. • Support firms in funding programs. • Universities as partners to develop environmental innovations. • Public policies and its influence in university industry collaboration. • The recent simplification of process for joint collaborations as well as intellectual property and start-ups spin-off management. • Ways to eliminate the cultural barrier to collaborations with university.
Triguero & Fernandez (2018) [27].	• Vital contribution of universities for specific science-based industries. • Universities as an attractive option for firms with less capacity of investment in innovation. • OI strategies which includes universities are increases the chances of success of innovation of new products and processes. • The higher knowledge, the higher innovation results.

The analyse of universities' best practices found some theoretical convergences about the university as a robust knowledge producer, innovation partner and as a protagonist of innovation. From the perspective of open innovation, most of the articles agree that university, at least theoretically, it is a protagonist regarding the initiative related to open innovation. Since there are many facets and outcomes offered by the university, the more are the match opportunities for societies´ demands.

Additionally, for the point of view of research and development, some studies point the university as a good solver of complexes problems, as a source of precise knowledge, and for hard sciences research and development.

Furthermore, the universities receive more deference of its work when the capability of research and development it is considered. The robust solutions offered by universities regard science - basic or applied, including high technologies, developed inbound or outbound, it is when it receives the higher levels of partners appreciation and reliability.

Other analysis of the content of this study contemplated the presence of Open innovation according to the Triple Helix context. The articles had its content analysed, and except by two works, all of them highlight the role and contribution of University, Industry and Government to innovation development separately as well as the interdependency and the balance between the interactions of these three actors to promote better environment and conditions for innovation. Table 3 shows the almost full presence of the Triple Helix actors discussed in the studied articles.

Table 3. Triple Helix mentions.

Author(s)	University	Industry	Government
Ebener, Liemiester & Krcmar (2009) [16]	Yes	Yes	
Spithoven, Frantzen & Clarysse (2010) [17]	Yes	Yes	Yes
Petroni, Venturini & Verbano (2012) [18]	Yes	Yes	Yes
López *et al.* (2014) [19]	Yes	Yes	Yes
Bianchi *et al.* (2014) [20]	Yes	Yes	
Gesing *et al.* (2015) [21]	Yes	Yes	Yes
Oguguo, Bodas & Genet. Al (2015) [22]	Yes	Yes	Yes
Bianchi *et al.* (2016) [23]	Yes	Yes	Yes
Rubera, Chandrasekaran & Ordanini (2016) [24]	Yes	Yes	Yes
Naqshbandi (2016) [25]	Yes	Yes	Yes
Greco, Locatelli and Lisi (2017) [26]	Yes	Yes	Yes
Triguero & Fernandez (2018) [27]	Yes	Yes	Yes

Even that almost all articles contemplate the relations university-industry-government; naturally, some of them give more attention to determining themes according to the scope of this study. However, it is convenient organise the articles which show more contribution to innovation when considered which one of the three Triple Helix actors. Independently of these different approaches, all of them cope with different management perspectives and levels.

All author of the following papers realises the benefits and outcomes of the collaboration of university-industry. There substantial importance of straight collaboration between research with firms and universities or public research organisations. (Spithoven). Firms which works with innovative activities and product innovation, tend to be more interested in collaborating with universities. Moreover, there are some

differences between the non-high-tech and high-tech firms. The second one shows more interest and opportunities to collaborate with universities than the other type. (Lopez)

Although the collaboration is imminent, the way that the firms manage these interactions internal and externally can be different and influenced by many variables. Furthermore, most of the studied articles highlighted how to manage human factors in detriment of methodologies by itself, such as described by the following authors. Firms should collaborate with external subjects to enhance the effectiveness and efficiency of internal research & development investments [26]. Just a consistent base of technical knowledge can guarantee the shift from the inter-functional integration of technology required for Open Innovation practices. This implementation requires a policy that supports all changes in managing scientific personnel [18]. The use of other companies as sources of information is an essential determinant of R&D intensity and, indirectly, of innovative output and revenue growth. Additionally, it seems that managerial ties with managers of other firms, universities/research institutions and government officials facilitate Open Innovation, and that can be realised by absorptive capacity. (Naqshbandi) Informal governance mechanisms such as relational trust, interfirm socialisation, and partnership reputation affect employees' attitudes toward external knowledge positively [21].

Finally, there are some studies which emphasises the understanding and management of information, structure profiles, internal and external policies, regional characteristics which support Open Innovation processes as described by these following authors. The interaction structures of such innovation communities require a deeper understanding of the antecedents, the structural elements, design parameters and the outcomes of idea competitions [16]. The nature of the determined markets and its learning curve demands the intervention of policymakers in order to make the innovations feasible. [26]. There are technological spill overs for R&D product innovation in the same sector, induced by geographical proximity [27].

Firms tend to develop capabilities to engage in networks of partners to access resources and inputs to advance their technology and product development in countries where firms are more exposed to institutional and economic incentives for organising innovation activities [22].

The last part of content analysis privileged the study of Product Lifecycle Management approaches. Even that the PLM keyword was present in all twelve selected articles, and an amount of them are clearly related to product development, the texts did not clearly mention the PLM approach in any of its phases. The developing of innovation regarding the PLM stage as Beginning of life, Middle of Life or End of Life was not considered or described. The articles presented mentions to research and development and innovation just as a general development perspective.

Conclusion

This paper mapped the universities best practices to deal with Open Innovation. Some authors are transparent in identifying factors that still impede the collaboration between the university and other actors. The complexity of relations, cultural barriers,

complexes solutions only, or hard sciences - high technologies profile, formalities and contract affairs, affect the way that potential partners con-sider universities for potential collaborations.

More than bureaucratic affairs, there is a challenging scenario which considers internal and external factor and the healthy relationship between then to move this big motor called Open Innovation. The complexity of the relationship surpasses laboratory capacity, enterprise investments or public policies. A considerable volume of pieces of information details enterprise architecture and human factors which con-verges in a proper culture for innovation should be the agenda for the leaders who want to implement or improve Open Innovation practices.

Many of the studied papers also indicate the university as a source of open innovation, but not only. It is growing the articles which consider suppliers, laboratories, research institutes, governments, consumers, as sources for open innovation. These initiatives that try to include as many as actors as possible in OI processes, to complementary results or even replacing universities roles. In these cases, R&D institutes, laboratories and other functions by its technical expertise or by other factors such as time-to-market orientation, or even less bureaucracy are replacing universities for similar collaborations.

When the analysis of these articles is made by the optical of Product Lifecycle, the relations university-industry are not clear. In general, the studied papers show the importance of the university in open innovation, indicating some interactions in product development; nevertheless, specifics or detailed contributions for PLM were not found. This factor indicates the opportunities for future studies, to understand Open Innovation considering university can cope with a PLM approach, observing characteristics that can better suit the innovation proposal for different stages. Mainly because of the scientific research and development which flourish within universities is composed of very high quality, however, very specialised solutions. There are opportunities to develop more comprehensive and combined approaches inducing more overtures as sometimes one university is not able to develop solutions for a whole product lifecycle.

The Open Innovation best practices considering universities as the protagonist of the innovation ecosystem found by this study are many: some methodologies, approaches, management styles, organizational architecture, and more. In summary, this study sought to identify the best practices of Open Innovation, finding gaps in the literature as well as in practice, and based on this finding, propose future studies to encourage Open Innovation in universities and their partners.

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Revisiting the Product-Process Matrix: incorporating distributed manufacturing concepts

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Abstract. With the advent of Industry 4.0 and all the technologies and concepts linked to it, a new reflection on the methodologies and concepts already established in the scientific scope and their usability with the insertion of these new technologies and concepts in the manufacturing environments is necessary. Industry 4.0 brings with it concepts of Distributed Manufacturing that work from information returns from the entire production chain and allow the production lines to act flexibly. The degree of flexibility of a manufacturing process is precisely one of the main variables of the Product-Process Matrix, a concept of a two-dimensional matrix created by Robert H. Hayes and Steven C. Wheelwright in the late 1970s in order to facilitate the understanding of options strategic aspects of an organization, particularly with regard to its manufacturing function. This work explores the impact of current industrial environment contrasted with a classic late 70s matrixial tool, highlighting its substantial differences, mainly regarding the flexibilisation of modern production lines. That way, it might be possible to comprehend how the product-process matrix, which is still used so far, behaves in relation to recent and future scenarios, also measuring its practical value.

Keywords: Product-Process Matrix, Distributed Manufacturing, Flexibilisation.

1 Introduction

The need for coordination between marketing strategy and manufacturing strategy has long been emphasized in the literature. A study by Woodward [1] emphasized the need for such coordination, although the focus of the study was on the classification of manufacturing companies. Skinner [2] emphasized the need to align manufacturing policy with corporate strategy so that the strength of manufacturing can be exploited to obtain a competitive advantage in the market. Subsequently, a relationship between the product life cycle and process innovation was proposed by Abernathy and Townsend [3] and Utterback and Abernathy [4]. The product life cycle has been studied in a wide range of organizational configurations. It focuses on the marketing implications of life cycle patterns, and this implies that other aspects of the business and industry environment move in concert with the market life cycle.

Later, based on these studies, Hayes and Wheelwright [5] brought the product-process matrix, which evolves from a fluid process - one that is highly flexible, but not very cost efficient - and continues to increase standardisation, mechanisation and automation.

Currently, the technologies of Industry 4.0 allow the achievement of higher levels of performance in quality, productivity, time and cost savings, with implications that directly impact the structure of the product-process matrix and advances that support greater industrial product flexibility through automation. Therefore, it is feasible to explore these paradigms brought by disruptive technologies, in an analysis of the applicability of the product-process matrix to current and future manufacturing scenarios. In this way, we will investigate the impact of Industry 4.0 technologies on the structure of the product and process matrix.

This work is structured as follows: Section 2 presents the main concepts to be addressed in the paper, namely the product-process matrix and distributed manufacturing. Section 3 introduces flexibility as the mediating effect for the realignment of the product-process matrix according to distributed manufacturing characteristics, and Section 4 further explores the mediating role of flexibility to revise the product-process matrix. Finally, Section 5 presents the conclusion of the work and some final remarks.

2 Theorical Background

To achieve a coherent conceptual framework, the revision of the Theoretical Foundations of the existing literature must be carried out. The basic terminology and theoretical foundations for this research are detailed in the following subsections.

2.1 Product-Process Matrix

The product-process matrix was proposed by Hayes and Wheelwright [5][6] to correlate the structures of the production processes with different product structures, as shown in Fig 1. In practice, the matrix helps to identify the types of production processes and their alignment with a company's products. A striking visual feature of the product-process matrix is that, when the production system analyzed is positioned diagonally across the matrix, this represents that a superior competitive performance has been achieved. In other words, it is assumed that there is an optimal combination of product and process.

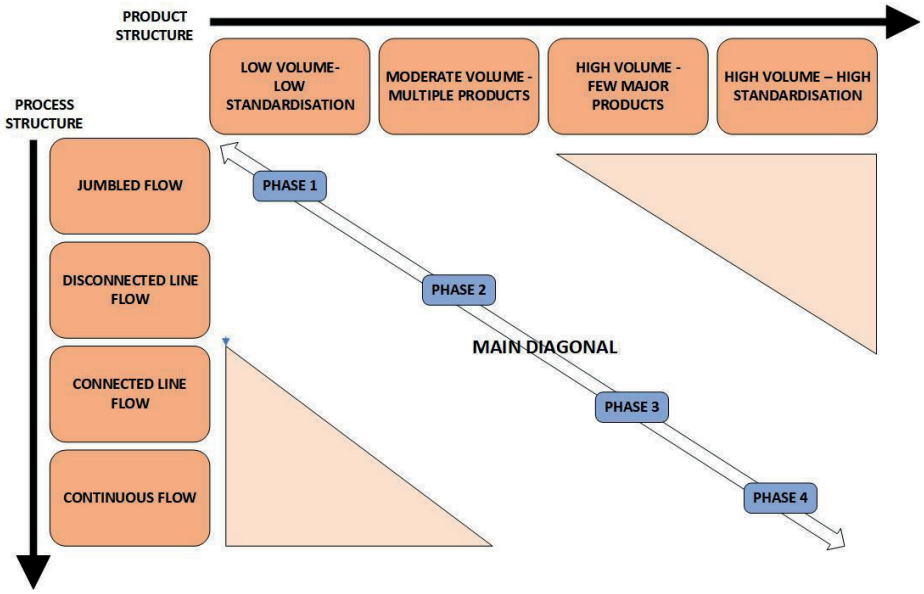

Fig. 1. The product-process matrix adopted by Hayes and Wheelwright [5].

The product-process matrix proposes four basic types of processes: job-based production, i.e., job shop; batch production; mass production, i.e., assembly lines; and continuous process production. A company can be characterized as occupying a certain region of the matrix, according to its product life cycle and its production process for that product. The product process matrix can be represented in 4 phases:

- *Phase 1:* When the company is positioned in the upper left corner of the product process matrix, it is characterized by having a unique product with a low manufacturing volume, with an undefined/confused manufacturing process. Another characteristic of this analysis suggests that the company has a low equipment occupancy rate, employees that multitask during the process and high production time.
- *Phase 2:* Following the matrix's main diagonal, slightly more to the right and to the bottom, the manufacturer usually chooses a production structure characterized as a "disconnected line flow" process. The company chooses to offer several products with basic characteristics, but with high variability. This allows the manufacture to go from a "Job Shop", to be considered a low volume assembly line.
- *Phase 3:* Even further down and diagonally to the right, it is a production model characterized by automobile manufacturers or large household appliances. Thus, the company opts for a relatively mechanized and connected production process. It is also characterized by a standardized and automated process to satisfy the product's life cycle and the company's savings.
- *Phase 4:* Finally, in the right corner of the matrix, we find examples of industries such as sugar or petroleum refineries, where the product is a commodity and the process is continuous. Its operations are characterized by being

inflexible and capital intensive, however their disadvantages are offset by the low variable costs resulting from a high volume that goes through a standardized process. At the time the original model was created, operationalization was well aligned with contemporary literature on organizational technologies. Therefore, the layout of the value adding process was a relevant contingency variable in the organization's design [8].

Notwithstanding, process technologies have changed significantly over the past three decades, and therefore the model must be updated to accommodate the flexibility of modern manufacturing technologies.

2.2 Distributed Manufacturing

With recent advances in Industry 4.0, production and infrastructure technologies allow manufacturing on a smaller scale with much greater proximity between the end user and the product, referred to as Distributed Manufacturing (DM). The concept of DM is not restricted to only fundamental manufacturing concepts, such as digitalisation and intelligent machines, but also to decentralisation of Manufacturing, where there is participation of the end user from the beginning of the project to production [9].

In a process of constant evolution analogous to digital transformation, the DM paradigm is characterized by new business models operating in "distributed economies" (Johansson et al., 2005). Those economies, whose small-scale flexible networks have a more local dimension, use materials and other resources that are also local, offering environmental benefits and leading to more sustainable forms of production. Thus, such sustainability directly impacts energy efficiency and resource-saving manufacturing systems [9],[10],[12].

The work of Srai [9] compares other manufacturing paradigms (Virtual Enterprise, Industry 4.0, Grid Manufacturing, Concurrent Engineering, Smart Manufacturing and Cloud based Manufacturing), recognizing five main characteristics of DM: (i) digitalization, (ii) personalization; (iii) location; (iv) new manufacturing technologies; and (v) multiuser participation. The scope of this research focuses on three characteristics of DM, not addressing 'location' and 'multiuser participation' as they are not directly related to the product-process matrix, being irrelevant by analyzing these characteristics from the perspective addressed.

3 Flexibility and its mediating effect

In the future, long-established paradigms of production will still have to continue to change to meet the demand for even more individuality, customer-specific product variants and shortest delivery times within the meaning of the term "production on demand" [12]. Skinner [2] claimed that there is a tradeoff among multiple manufacturing competitive performances in his landmark paper on manufacturing strategy; therefore, firms have to focus on some type of performance such as quality, dependability, and cost, which are critical for the attainment of the strategic objective [5], provided the product–process matrix to emphasize the importance of the cooperation of

manufacturing (processes) and marketing (products) to achieve the unified goals based on Skinner's tradeoff theory [33]. Gunasekaran *et al.* [34] defend that to a greater extent, the investigation of the product-process interplay in technology-enabled manufacturing paradigms offers tailored quality management practices and fulfill the expectations of global customers. Despite that, Ariss and Zhang [33] defends that environments have dramatically changed, and recently, some studies have empirically verified that a firm can achieve multiple competitive performances simultaneously. Thess studies especially illustrate how the high flexible process capability that a firm possesses greatly enlarges the feasible zones and reduces the constrained zones in the product–process matrix.

In today's highly competitive global business landscape, customers demand personalized products and responsive distribution systems, hence fueling the concept of Distributed Manufacturing (DM) as a paradigm that suggests the geographical distribution of manufacturing systems adjacent to the markets enable 'production on demand' [5]. This study's objective is to make a theoretical comparison of the main concepts of DM and the product-process matrix by the lens of a common denominator – flexibility – and understands how the new technologies of DM and Industry 4.0 will change the way that relationships between product and processes are seen.

3.1 The flexibility concept

According to *Oxford Dictionaries, s.v.* "flexible," accessed August 12, 2020, https://www.lexico.com/definition/flexible; means capable of bending easily without breaking - and more specifically, in context with the proposed question - able to be easily modified to respond to altered circumstances.

A manufacture which can be easily modified will improve a firm's abilities to react in timely manner to customer demands and to increase production system productivity, without incurring excessive costs and expending an excessive amount of resources. Ultimately, market and industry trends favor a higher product mix and fast responsiveness to demand changes and static business models are no longer able to keep pace with such change, forcing business processes to become more dynamic, requiring more flexibility [29] + [30]. In an interview research, [31] highlights the need for companies to see process improvement as one of its main drivers, expecting that it leads to quality and output improvement as well as time-savings and a higher adaptability of production**.**

Nonetheless, one difficulty in designing flexible production lines in the age of Industry 4.0, is the huge amount of product mix and existing production systems. In the past, companies in process industry sold single products in standard size and packaging. Today, companies are advertising a higher variety of products and selling them in different packaging sizes [29]. By automating, standardizing and globally sourcing processes, organizations can become more agile, more responsive to changes in demand, and better able to increase and sustain profitability [32]. In the context of the product-process matrix, Increasing the product mix challenges the ability of production systems to maintain high productivity.

The process life cycle was presented by Hayes and Wheelright in late seventies to be compared with the product life cycle and form the bidimensional matrix that is well known nowadays as the product-process matrix. Just as a product and market pass through a series of major stages, so does the production process used in the manufacture of that product. The process evolution typically begins with a "fluid" process—one that is highly flexible, but not very cost efficient—and proceeds toward increasing standardization, mechanization, and automation. This evolution culminates in a "systemic process" [5]. The main characteristics of this concept is that it becomes less flexible at each level.

However, accordingly to Ariss & Zhang [33] flexible manufacturing systems have allowed some assembly/continuous flow shops to achieve customisation in mass quantities. Moreover, some batch shops use similar methods to produce standardized products in moderate to high volumes. Therefore, flexible capability changes the feasible region of the product–process matrix from the solid line to the dotted line, as seen in Fig. 2.

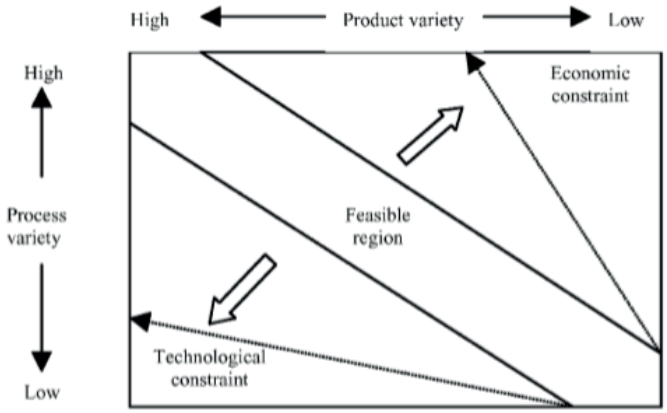

Fig. 2. The effect of flexible capability on the product-process matrix (based on Ariss & Zhang [33]).

Weraerfelt [35] presents the concept of flexible process capability, which changes the feasible region in product–process matrix, and argues that strategic analysis should shift its attention from industry forces and product market positioning to developing and exploiting the unique set of resources (such as technical and organizational skills) upon which a firm's long-term profitability depends.

Distributed Manufacturing is particularly characterized by technological developments in engineering and computing that bring new capabilities to manufacturing in terms of automation, complexity, efficiency, and most of all, flexibility. Following Kohtala [10], DM takes the perspective of production planning for networked or "virtual" enterprises aiming for flexibility, agility and greater customer orientation in manufacturing and mass customization.

The concept of Distributed Manufacturing enhances flexibility in modern industries with help of its three main characteristics, as explained in the next section.

3.2 Key characteristics of Distributed Manufacturing and their relationship to flexibility

The components of this DM characteristics (see Fig. 3) as seen in Kumar [7] are levels that enable its applicability and are defined below:

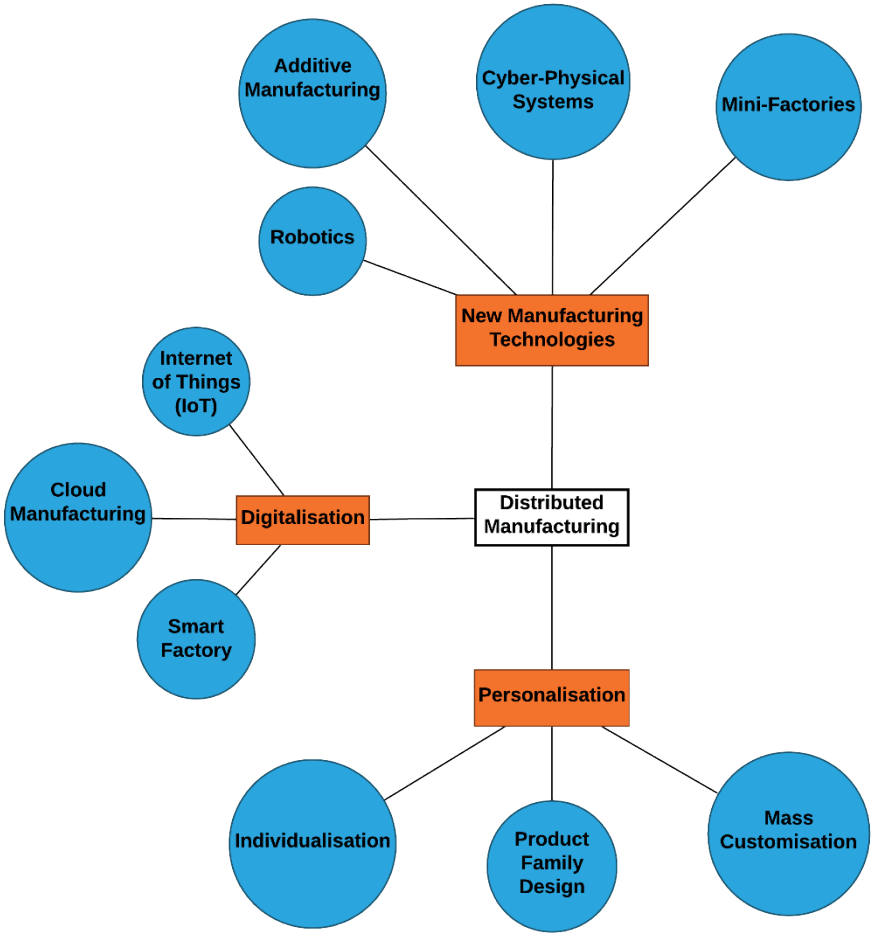

Fig. 3. Mind map of the concepts of DM, its components in blue, and characteristics in orange (based on Kumar [7]).

Digitalisation. Digitalisation of manufacturing implies the integration of information and knowledge between production and planning levels, further expanding to customers and suppliers [13]. The definition of its components is seen next.

- *Internet of Things (IoT).* IoT in manufacturing, from a technical perspective, envisions to connect every element of a manufacturing system to the Internet and provide, from a practical viewpoint, context-sensitive information to the

right people at the right time to propel the related decision-making process [14].

- *Cloud Manufacturing.* The Cloud Manufacturing or Cloud Computing aims at integrating autonomous agents, multiple clients, and various suppliers on a single cloud platform to optimize manufacturing operations [15].
- *Smart Factory.* Smart Factory comprises a set of smart machinery and conveyers that can communicate with each other to reconfigure dynamically for enabling the flexible production of multiple product types [16].

Personalisation. Direct consequences of digitalisation, which facilitates the modification, both subtle and extensive, of physical products [9].

- *Individualisation.* The Individualisation strategies aim to satisfy each customer as an individual with implicit needs so that the final product, as well as the basic design and product structure, are changeable, adaptable, configurable, and consequently less predictable [20].
- *Product Family Design.* Product Family Design aims for sufficient external product variants combined with manageable internal variety to obtain economies-of-scale at the component level and to reduce complexity in the development and manufacturing capabilities [21].
- *Mass Customisation.* Mass Customisation aims to fulfil individual customer needs at a cost level that satisfies a large share of the market [22].

New Manufacturing Technologies. Enable product variety at multiple scales of production, and as they mature, promise resource efficiency and improved environmental sustainability [9].

- *Robotics.* Robotics or robot technology could be described as intelligent artificial beings, typically made of metal, capable of executing intellectually demanding human tasks [36].
- *Additive Manufacturing.* Additive manufacturing, widely referred to as 3D printing, suggests that a technical design, generated using a three-dimensional computer aided design system, can be fabricated directly without the need for process planning [37].
- *Cyber-Physical Systems.* Cyber-Physical Systems are defined as the systems where the physical and software components are intertwined, operate on different spatial and temporal scales, exhibit multiple and distinct behavioral modalities, and interact in a myriad of ways that alter with context [38].
- *Mini-Factories.* Mini-Factories are flexible and rapidly reconfigurable small-scale factories for the geographically distributed manufacturing of products ensuring both product and quantity flexibility [12].

4 Realigning the product-process matrix to distributed manufacturing concepts

Is it possible that the Distributed Manufacturing concepts will allow the feasible region of the product-process matrix, early kept only in the main diagonal of the matrix, to expand and encompass all the model quadrants? The answer seems to be yes. Hayes & Wheelright [5] deduced that the process evolution typically begins with a natural process — one that is highly flexible, but not very cost efficient— and proceeds toward increasing standardization, mechanization, and automation. This evolution culminates in a "systemic process" that is very efficient but much more capital intensive, interrelated, and hence less flexible than the original, more natural process. For example, the key competitive advantage of a jumbled flow operation is its flexibility to both product and volume changes. As one moves toward more standardised processes, the competitive emphasis generally shifts from flexibility and quality (measured in terms of product specialisation) to reliability, predictability, and cost [5]. The authors of the product-process matrix would say that the corners of the matrix are void of industries and companies because, for the upper right the process are not economical, end for the lower left the process are too inflexible, therefore Ariss & Zhang [33] make two assumptions: (1) within a given technology, manufacturing is able to do everything; and (2) manufacturing's contribution concerns the achievement of efficiency rather than the effective support of market needs.

Taking these assumptions into consideration, perhaps the concepts and characteristics of distributed manufacturing could help improve the feasible zone with flexible characteristics and yet establish a sustainable competitive advantage. Considering that the flexible capability changes the feasible region of the product–process matrix from the solid line to the dotted line as proved by Ariss & Zhang [33] (see Fig. 2), it's possible to use the concepts of Digitalisation and Personalisation to improve the feasible zone, while the new technologies will serve as a base to development, as seen in Fig 4.

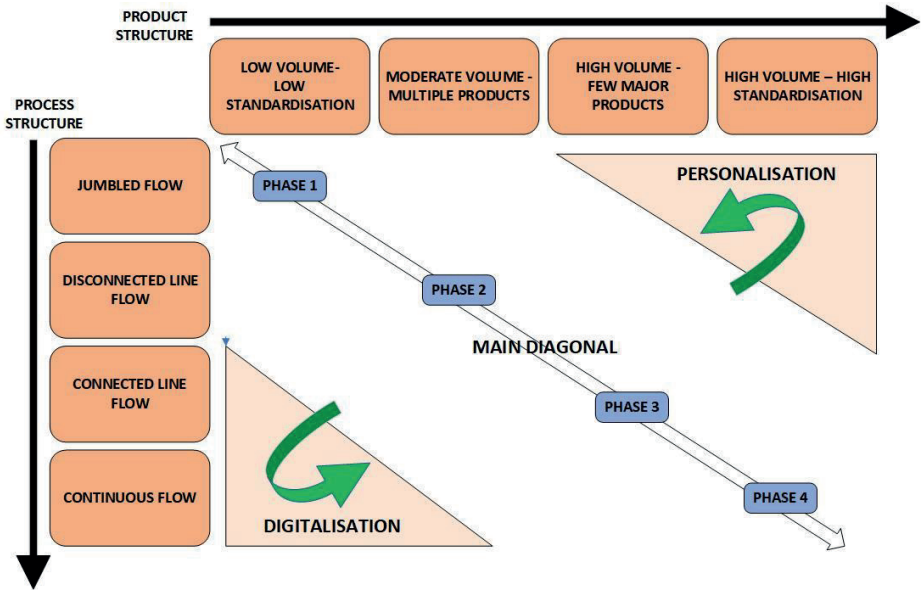

Fig. 4. Personalisation and digitalisation in product-process matrix.

In this situation, it is possible to dismantle the concepts of digitalisation and personalisation into its main characteristics and easily identify which of these characteristics could help improve each space of the matrix, looking from the process lens. Fig. 5 shows the first phase of process life cycle stage aligned with these concepts, where individualisation can help improve the link between the first phase with product phase 2, mass customization linking with product phase 3 and product family design with product phase 4.

	Low volume - low standardization, one of a kind	Multiple products - low volume	Few major products - higher volume	High volume - high standardization, commodities
Jumbled Flow		Individualisation	Mass customisation	Product family design

Fig. 5. First stage of the matrix with personalization concepts.

Using the same criteria, it is possible to link phase 2 and 3 of the process axis with upper diagonal correspondent phases of product axis, as shown in Fig. 6 and Fig 7. In these cases, its already possible to identify the lower diagonal as well. For these spaces, the main characteristics of the digitalisation concepts are used, following the same idea of Fig. 5.

	Low volume - low standardization, one of a kind	Multiple products - low volume	Few major products - higher volume	High volume - high standardization, commodities
Disconnected line flow (batch)	Smart factory		Mass customisation	Product family design

Fig. 6. Second stage of the matrix process axis with personalisation and digitalisation concepts.

	Low volume - low standardization, one of a kind	Multiple products - low volume	Few major products - higher volume	High volume - high standardization, commodities
Connected line flow (assembly line)	Smart factory	Cloud manufacturing		Product family design

Fig. 7. third stage of the matrix process axis with personalisation and digitalisation concepts.

At last, in the final phase of the process axis of the matrix is linked at each phase of the product axis by all the main characteristics of the digitalisation concept, as shown in Fig. 8

	Low volume - low standardization, one of a kind	Multiple products - low volume	Few major products - higher volume	High volume - high standardization, commodities
Continuous flow	Smart factory	Cloud manufacturing	Internet of things (IoT)	

Fig. 8. Fourth stage of the matrix process axis with digitalisation concepts.

The final assembly of the matrix aligned with distributed manufacturing concepts can be seen in Fig 9.

	Low volume - low standardization, one of a kind	Multiple products - low volume	Few major products - higher volume	High volume - high standardization, commodities
Jumbled Flow		Individualisation	Mass customisation	Product family design
Disconnected line flow (batch)	Smart factory		Mass customisation	Product family design
Connected line flow (assembly line)	Smart factory	Cloud manufacturing		Product family design
Continuous flow	Smart factory	Cloud manufacturing	Internet of things (IoT)	

Fig. 9. Full aligned product-process matrix.

5 Conclusions and Final Remarks

As one of the great standards of strategic operations management, it is impressive how the product-process matrix managed to stay as the main model of production relations, but it seems that the brand new concepts and technologies of industry 4.0 can help evolve the vision presented by Hayes and Wheelright in a great manner, increasing the feasible zone of the matrix and helping stakeholders all around the world to keep the production strategy up to date and better able to increase and sustain profitability.

This revisited Product-process matrix can help researches to discover possibilities of technological implementations that better suits into company strategy, taking into account the company size and its manufacturing proportions, as well defined by the matrix, and correlate the structures of the production processes with different product structures. The defined concepts of distributed manufacturing can help mapping the opportunities of any phases of production and connect it to this new concept trends and show to the stakeholders a holistic view of the implementation roadmap.

For future studies, the conceptualisation of a possible framework could be an advance to help keeping the matrix up to date, or even reconfigured for a present perspective. Industry 4.0 technologies may guide further research and encourages practitioners to consider them in their current and future activities.

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Integrated production and maintenance planning: a systematic literature review

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Abstract. Production and maintenance planning are interconnected problems, so that their joint solution can enhance system performance. This paper develops a systematic review on the integrated production and maintenance planning on manufacturing systems. The content analysis included sixty-nine papers, embracing aspects of production system modelling, optimization mechanism, practical applications and research directions. The findings indicate the predominance of theoretical studies, the use of genetic algorithm for the optimization engine, in which costs and makespan are the variables of the objective function. Future research directions point to applications for real scenarios, predictive maintenance and models with increasing complexity.

Keywords: Production planning and control, Maintenance scheduling and production planning, Maintenance models and services, Modelling and decision making in complex systems, Modelling of manufacturing operations, Production scheduling, Meta-heuristics.

1 Introduction

In production environments, machines are not always available as they are subject to periods of downtime due to planned and unplanned shutdowns [1-2]. Considering the dynamic and stochastic nature of failure occurrence, production planners and managers have complex decisions to deal with on a daily basis [3-4]. Aiming to speed up production, recommended maintenance intervals are often poorly planned [1].

Production and maintenance scheduling have attracted great practical and academic interest, however those problems are commonly treated as independent [5-6]. Notwithstanding, literature has shown that developing the production planning and control integrated with the maintenance planning can benefit several production performance indicators [7-8]. Indeed, manufacturing systems generally show a natural in-

terdependence between production and maintenance activities, which raises the question of how to optimize them jointly to avoid conflicts and improve system performance [9].

A large number of studies about production and maintenance were carried out, however, almost all of them considered these as two independent problems. Only a few studies tried to combine the two issues to solve them simultaneously [7]. In addition, the criticality of resources may change depending on the production planning being conducted. Therefore, there is a need to coordinate production and maintenance planning tasks, which incorporate potential cost minimization [9].

The objective of this article is to perform a systematic review of the literature regarding the current models that integrate production planning and control with maintenance planning. This systematic review can allow the acknowledgment of existing studies in the field and, the identification of research gaps, helping to prevent the production of duplicate works [10]. Besides, it can provide several insights from the state-of-the-art literature, including common practices and research directions.

The systematic review intends to answer three research questions about the subject: (i) how did the studies on integrated production planning model the production system and the optimization process? (ii) which studies modelled real scenarios for integrated production and maintenance planning? (iii) what are the main directions for future research?

The remaining of this paper is structured as follows. Section 2 shows the research method of the systematic review and bibliometric analysis. Section 3 shows a brief bibliometric analysis, followed by the systematic review in Section 4, which is divided accordingly to the research questions. Finally, section 5 presents the discussion and proposals for further research.

2 Research Method

The conducted systematic literature review followed the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) approach, which is proposed by [11] and is the most commonly used for reporting literature review [12]. It was first applied in health care studies but is also suitable for many areas, including industrial engineering [13-14].

The paper selection step used the following search logic: (TITLE-ABS-KEY(("Produ* plann*" AND maint*) OR ("Produ* Sched*" AND maint*) OR ("Manufac* plann*" AND maint*) OR ("Maint* plann*" AND (Produ* OR manufacture*)) OR ("Maint* Sched*" AND (produ* OR manufacture*))). The search was performed in two databases: Scopus (www.scopus.com) and Web of Science (www.webofknowledge.com).

The process for selecting papers is shown in Figure 1. After the identification of the papers, duplicates were removed. The criteria for inclusion and exclusion of papers are presented in Table 1, following the ones used by [15], and were applied by reading titles, abstracts and keywords only. The remaining papers in the last stage were eligible for the content analysis, i.e. the qualitative synthesis.

Table 1. Inclusion and exclusion criteria.

x	Criteria	Criteria explanation
Inclusion	Closely related (CR)	Time period: prior to April 2020; Articles that were published until 2014 were included only with more than 5 citations according to Bibliometrix.
Exclusion	Search engine reason (SER)	The article has only the title, abstract and keywords in English, but not the full text in English.
	Without full-text (WF)	The full-text of the article is not available.
	Non-related (NR)	NR1: It is not an academic article; NR2: It is not aligned with "integrated production planning model with maintenance".
	Loosely related (LR)	The article does not focus on discussing the development of an integrated production planning model with maintenance. More specifically: LR1: It is used only as an example; LR2: It is used only as part of its future research direction; LR3: It is used only as a quoted expression; LR4: It is used only in keywords or references; LR5: The research that does not address the context.

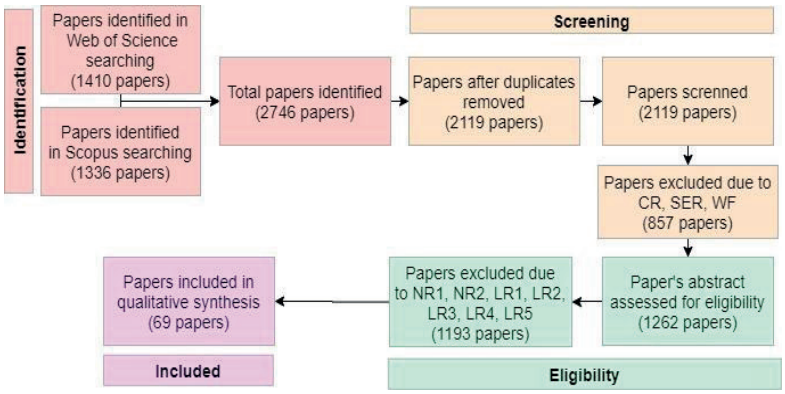

Fig. 1. Systematic review process.

From the articles included in the content analysis, we performed a brief bibliometric analysis pursuing to better understand the scientific activity through time and among different journals and research groups. Such analysis was aided by the Bibliometrix package developed in R programming language [16], more specifically using the Biblioshiny interface and the RStudio© integrated development environment.

3 Bibliometric Analysis

From the analysis of the bibliometric data, Figure 2 shows the temporal evolution of the publication of the articles included in the analysis of this research. The first article was published in 2000, and starting in 2010, there is a tendency of publication volume increase. Although the largest number of publications are in the last decade, the number of published articles has fluctuated between 1 and 11 per year. It is also noteworthy that the year 2020 is incomplete because of the date when the search was performed.

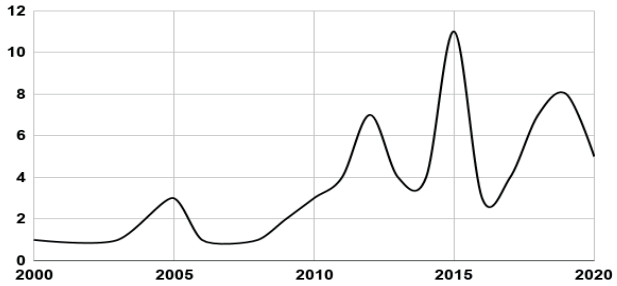

Fig. 2. Increase in publication quantity per year.

Most of the selected papers were published in the International Journal of Production Research with 9 occurrences [17-25], in sequence, International Journal of Advanced Manufacturing Technology with 5 papers [26-30]. The paper [31] has the highest number of citations (135) in other studies. The second with the highest number (90) of citations [32] is by the same author. Both are articles about potential studies for the topic presented here. Considering the scientific production by countries, we can highlight that China is ahead with 21 published papers, next we have Canada with 11 and France with 8.

4 Systematic Literature Review

This section addresses the research questions: (i) how did the studies on integrated production planning model the production system and the optimization process? (ii) which studies modelled real scenarios for integrated production and maintenance planning? (iii) what are the main directions for future research?

4.1 How did the studies on integrated production planning model the production system and the optimization mechanism?

Integrated production and maintenance planning have been treated as an optimization problem, having been addressed by several solution methods. Table 2 shows the quantity and types of methods that were used to solve the models in the literature.

Table 2. Resolution methods.

Resolution Method	Paper
Branched exploration algorithm	[33]
Genetic algorithm of approximate non-dominant classification II	[39]
Best fit descending algorithm	[40]
Optimization based on biogeography	[46]
Optimization of hybrid genetic algorithm	[5], [61]
Hybrid ant colony optimization	[5]
Mixed integer linear programming	[17], [50]
Differential evolution method	[47]
Annealing simulation method	[47]
Randomized research method	[47-48]
Experiences project	[48]
Artificial immune algorithm	[70]
Simulated annealing algorithm	[38], [65]
Harmony search algorithm	[50]
Vibration damping optimization algorithm	[50]
Pseudo-polynomial programming algorithms	[71]
Evolutionary genetic algorithms multiobjective	[74]
Non-dominated genetic classification algorithm II	[20-21], [27], [74]
Algorithm based on multi-objective optimization of ant colonies	[72]
Pareto ant colony optimization	[27], [72]
Stepwise optimization method	[52-53]
Policy improvement algorithm	[19]
Dynamic programming	[25]
Dantzig-Wolfe decomposition technique	[54]
Continuous resource task network	[55], [80]
Chaotic particle filling optimization algorithm	[77]
Clonal immune selection algorithm	[59]
Mixed linear model	[24], [37], [64], [67-68]
Hybrid particle swarm optimization	[27]
Pareto force evolutionary algorithm II	[20], [27]
Linear quadratic model	[18]
Branch and limit algorithm	[21], [31]
Optimization-based simulation	[46]
Genetic algorithm	[1], [22-23], [34-35], [41], [46], [49], [51], [57], [69], [73], [75-76], [78-79]
Other heuristics	[7], [9], [19], [26], [28-29], [32], [36], [38], [42-45], [56], [58], [60], [63], [66]

There is a predominance (18,1%) in the use of genetic algorithms (GA), which also appears in approaches combined with other heuristics. These studies that applied the use of a genetic algorithm conceptually validate their application, since they achieved good results, but still need better development, according to the authors. The use of heuristics (other heuristics) created by the authors themselves is also relevant, with 22,9% of the total. The literature is quite comprehensive and there are several methods of resolution, all with different characteristics and applicability. Comparing methods present in the literature can be a good question to find the best result. We can also analyze that in some papers, more than one method was used

The desired objective in each approach present in the literature also varies. Cost-related indicators were used as key performance indicator (KPI) for optimization in 71% of all articles. The use of cost as a KPI in the optimization method facilitates the aggregation of different variables in the composition of the best solution, such as cost of maintenance, production and delivery delay to the customer. Among them, few articles address the cost of quality, delay and stock in addition to the production and maintenance costs. The second most used KPI was makespan (29%), and system availability is considered in four papers.

In some articles, in order to model the useful life behavior of machines and production systems, or their deterioration process, different forms of representation are used. In Figure 3 we analyzed the articles that included machine deterioration processes (55% of the total). The predominance was of criteria adopted and elaborated by the authors themselves. Another one with greater use was the use of Weibull Distribution and its combination with Gamma Distribution.

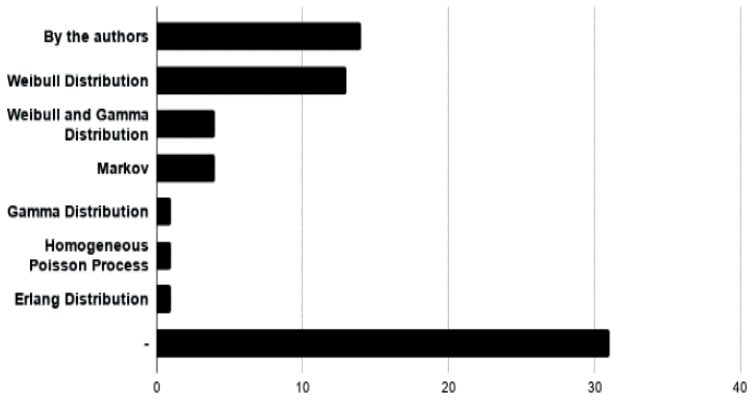

Fig. 3. Number of papers in relation to the deterioration method.

In Figure 4, the articles were classified according to the type of productive system modeled. The predominance of single machine models is evident. Nowadays, with all the technological advances, the production processes become more complex every day and with significant machine interaction.

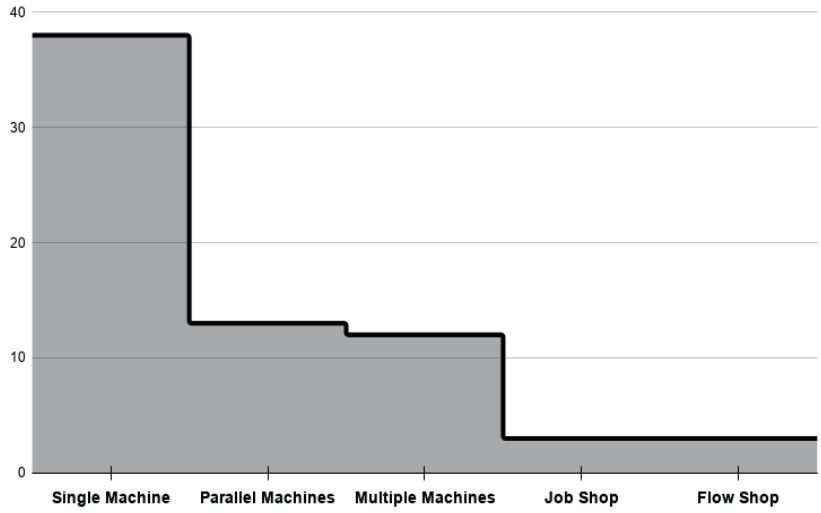

Fig. 4. Number of articles in relation to the type of production of the model.

4.2 Which studies modelled real scenarios for integrated production and maintenance planning?

Only the papers [7, 17, 28, 33-38] developed and applied a model considering a practical case of application, i.e. 13%. The rest of the papers (87%) did not apply in a real production scenario [1, 5, 9, 19-27, 39-80]. The same authors who applied in real scenarios, reinforce the need for this type of application in order to validate the efficiency of the method, so that it can be replicated by other industries and start to be better improved.

Among these studies applied in real production systems, the models [34-35] used the genetic algorithm as a resolution method, while the rest used other heuristic methods of resolution. Moreover, these authors still point out the need for an approach that uses methods able to adapt to different scenarios. These applied cases brought relevant KPI's improvements. In Table 3, we can see the main gains of the models applied in a real scenario.

Table 3. Gains from applying the method.

Reference	Results
[7]	Reduction in general production costs, because rescheduling efforts, rework and scrap, as well as inventory were reduced.
[17]	Costs reduced by up to 63.5% compared to the company's schedule.
[28]	Information for the managers to be able to make decisions, the paper did not bring an exact result.
[33]	Charts to show that, by applying the method, costs can be minimized and production maximized.
[34]	Limited their study in an injection company related to the maintenance of these molds, obtaining a 44.9% reduction of the production delay
[35]	The results obtained validate the efficiency of the new heuristic method.
[36]	Minimization of operating costs and maximization of the company's profit.
[37]	It allows you to decide which products need to be produced and the exact amount of production in each period and the best date for maintenance can be set. Production quantities were also influenced by the cost of inventory and the cost of back orders for different products.
[38]	80% savings. The numerical example indicates that an integrated model proposal performs better than stand-alone models.

4.3 What are the main directions for future research?

52 out of the 69 papers present future proposals for research to be developed. Many authors refer to the need for future research to focus on real cases for practical validation [5, 31, 41, 43, 47, 53, 61, 63, 71, 77, 79].

Also, many papers point to the demand for applications in more complex production scenarios, e.g. with different behavior patterns and production systems that use more than one machine [1, 20, 29, 32-33, 35, 37-41, 50, 63, 66, 68, 74-75]. Such demand was also observed in our systematic review, as explored in the first research question of this work. In [5, 63] the model developed is limited to a scenario with deterministic behavior; thus, the authors report the need for extension in unplanned and planned environments with stochastic situations.

For [9, 20, 22-23, 33, 37, 39, 44, 50, 66, 78] a strategic predictive maintenance policy needs to be better used in models so that it can allow the prediction of equipment deterioration in an environment with complexity to optimize machine availability. In [7, 21, 26, 43, 67-68] the authors state that methods of predicting maintenance failures should be better considered in new models.

For [17, 29, 49, 66], there is a necessity to improve the procedures for choosing and applying heuristics, since different choices may bring different results for a same model. In [20, 27, 45, 64, 73] the authors indicate meta-heuristics investigation for solving their models because it has potential for effective gain. In article [46] the use

of optimization-based simulation approach has had good results and has a potential for application in other contexts.

The study by [72] highlights the importance of developing other methods that evaluate the application of genetic algorithm hybridization, since it presents potential to efficiently solve these problems. In [58, 74], the authors encourage the study of more complex methods such as multi-objective optimization of ant colonies to solve new models as well as perform a comparison with Pareto Ant Colony Optimization, in [22, 24], they intend in future research to solve problems with greater complexity using the relaxation method and hybrid considerations. In the same way, the genetic algorithm has potential for new research because it presents good results in initial tests. In summary, we can see in Figure 5 a summary of the main directions of future research reported here in this section.

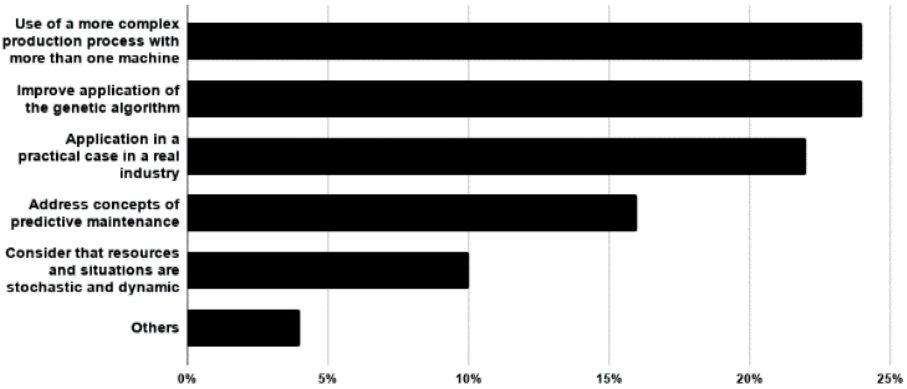

Fig. 5. Percentage of the main future researches reported by the authors.

5 Discussion

The conducted systematic review addressed the research questions and contributed to a better understanding of the field, considering modelling aspects, applications and research directions.

In summary, by analyzing the directions indicated by the papers in the portfolio and the trend of the papers over time, it is possible to identify some opportunities. Despite the predominance of the use of preventive maintenance for the integration of production and maintenance planning, the development of predictive approaches has increased.

There is extensive use of different heuristics in the optimization problem. The use of hybrid approaches appears as an opportunity to be further developed in this topic. As for the study environment, research that considers the production systems as a whole (most research considers only a single machine), and the application in real environments can still be better developed and only one paper was found that used an optimization-based simulation approach.

Analyzing other aspects and selecting other keywords to apply the literature review methodology of the proposed subject may be a good way, trying to seek other results. The interest in seeking the development of a model that integrates production planning and control with maintenance in a way that can be replicated in various contexts of the productive environment ends up being a challenge for future models.

In a next study by the authors of this paper, the application of these final analyzes in a conceptual and practical context is motivated, aligning these two requirements and being able to bring through the application positive results that may contribute to the subject.

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Development of a Methodology to Analyze Implementation Patterns of Industry 4.0 Technologies

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Abstract. The concept called Industry 4.0 has a very complex technological architecture based on Cyber-Physical Systems (CPS), which represents one of the main concerns in the start-up stage at an industrial level. The effective implementation of Industry 4.0 technologies continues to be a research topic. Some works propose maturity models for the implementation of these technologies, while others focus on the study of their impact on industrial performance. However, there is a lack of studies that provide evidence on the way in which these technologies are implemented in manufacturing companies in general. This fact leads to the following question: What are the current implementation patterns (degree of implementation – maturity stage) of Industry 4.0 technologies in companies? To answer this question, this work proposes the development of a tool for maturity assessment which allows understanding what is required to carry out an effective analysis of implementation of Industry 4.0 technologies in manufacturing companies by studying the degree of implementation – maturity stage in companies from different sectors.

Keywords: Industry 4.0, Maturity Assessment Tool, Maturity Model.

1 Introduction

The Fourth Industrial Revolution – also named as Industry 4.0 – is characterized by a fusion of advanced technologies that is disrupting almost every industry in every economy [1].

Industry 4.0 is a German strategic initiative whose main objective has been to create smart factories, where manufacturing technologies are updated and transformed through Cyber-Physical Systems (CPS), Internet of things (IoT) and Cloud Computing [2, 3, 4].

The fundamental idea of Industry 4.0 is based on integrating manufacturing systems of different smart factories along a value chain, or a value network, in the form of CPS so that data and information can be obtained in real time throughout the value chain, allowing time and precise decision making [5]. Moreover, the CPS are defined as transformative technologies to manage interconnected systems among their physical assets and their computational capabilities [6]. The competitive nature of today's industry

forces more factories to implement high-tech methodologies through recent developments that have resulted in greater availability and affordability of sensors, data acquisition systems, and computer networks [6, 7].

Industry 4.0 comes from the need to improve the means of production in a context of high emergence of new technologies in the field of information technology. It corresponds to a strategic program with the objective of developing production systems, thus improving the efficiency of the industry [2].

An important part of this program fits with the concept of Smart Manufacturing, which corresponds to a great flexibility of the production lines that can adapt to any change in products or conditions, ensuring an increase in quality and productivity [8].

Another part of the program focuses on Smart Working, i.e., the role of human workers that needs to evolve with the help of robots, which could fulfill difficult tasks and also make decisions through communication networks among them [9].

The exchange of information also represents a challenge for this new industry. Whether it is with customers, suppliers or other companies, this concept of Smart Supply Chain allows reducing delivery time and possible falsification of information. Furthermore, communication with other companies contributes to the targeting of their resources on the subject of innovation, working together to limit false leads and accelerate the development of technologies [10].

The last part of the program is given by integrated-embedded technologies which are called Smart Products, whose information is fed back from the final products, with the aim of improving and detecting possible production defects, developing new products and solutions to the customer [11].

Industry 4.0 technologies can be separated into the following layers [12]:

A) Front-end technologies of Industry 4.0 which considers the transformation of manufacturing activities based on emerging technologies (Smart Manufacturing) and the way in which products are offered (Smart Products) [8]. The way in which raw materials and the products are delivered (Smart Supply Chain), as well as the new ways in which workers carry out their activities based on the support of emerging technologies (Smart Working), are also contemplated.

B) Base technologies which comprise technologies that provide connectivity and intelligence for Front-end technologies. This layer makes the Industry 4.0 concept feasible, differentiating it from previous industrial stages.

This work presents the development of a Preliminary Maturity Assessment Tool (PMAT) that is used to identify technologies related to Industry 4.0, and to verify their degree of implementation – maturity stage in companies from different sectors.

This approach is considered as the first step for future research works, and consists of a Questionnaire that includes three types of questions: A) Basic; B) About technologies; and C) Open. The first and second types are closed questions and include a 5-point scale: 1) Non-existent; 2) Low; 3) Medium; 4) High; and 5) Very High. This scale indicates the level and degree of implementation – maturity stage.

The PMAT – Questionnaire is based on two propositions – hypotheses which are presented in Section 3 and guide to establish the points of interest and to develop more concrete and clear questions.

Section 2 depicts the research methodology which consists of multiple–case studies, and the propositions – hypotheses (PHs) constitute the units of analysis (UAs). Section 4 shows the analysis of the results, while Section 5 presents a discussion by including a comparative analysis of different maturity models of Industry 4.0. Finally, Section 6 develops the conclusions.

2 Methodology (Multiple – Case Study)

Based on the methodology of multiple – case studies with many units of analysis (UAs) [13], this methodology is proposed as a part of the first phase of a research project that aims to study the implementation of technologies related to Industry 4.0 in the region under analysis. For this purpose, four case studies have been selected representing different industrial sectors (see Fig. 1).

For each case study three units of analysis are considered, in which two of them are directly connected to the propositions - hypotheses (PHs) that are described in Section 3.

The choice of a qualitative methodology allows us to analyze in greater detail certain characteristics related to Industry 4.0 that are being implemented in the region, as well as to give us the first approach for future studies using other types of qualitative or quantitative methodologies.

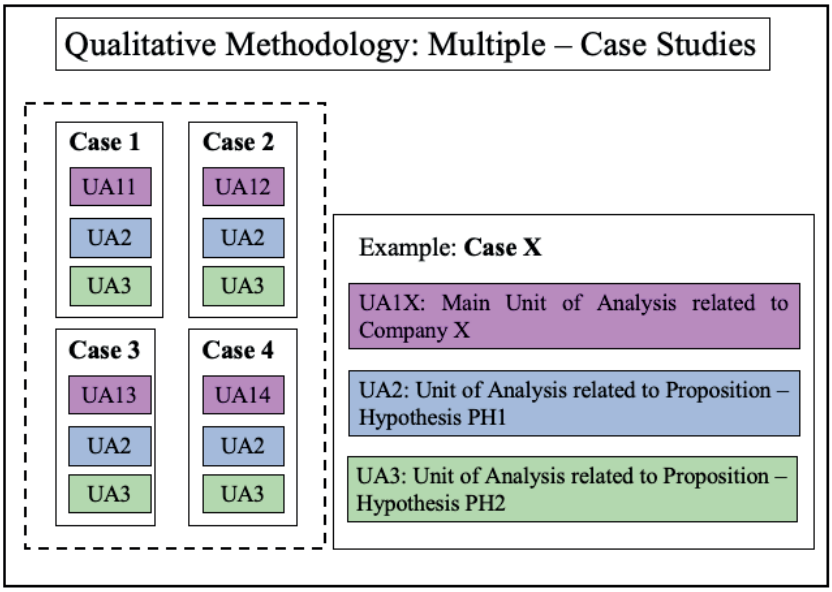

Fig. 1. Methodology of multiple – case studies with many units of analysis (UAs).

2.1 The Companies

In the current phase of the research project focused on Industry 4.0 in the Santa Fe region, fifteen companies were analyzed to apply the methodological process.

After studying several characteristics, such as size and clusters, four companies were finally selected with which it was possible to complete an exhaustive questionnaire that is described later.

Tables 1 and 2 show the clusters and the size, respectively.

Table 1. Industrial clusters of the companies under study.

Cluster	Percentage
Textile	25
Equipment manufacturing	25
Software and technology	50

Table 2. Size of the companies under study.

Size	Percentage
SME (<100 employees)	75
Large (>100 employees)	25

Thus, the research group has had the opportunity to study companies that had totally different activities and sizes from each other.

In this way, it was also possible to classify them according to the type of activities and form three "clusters" that helps to exploit the results.

In addition, the research group chose several characteristics describing the companies that make up the clusters that allow to explain several differences in the results that can be observed in Section 4 (analysis of results).

2.2 The Characteristics

The selected characteristics are detailed below.

Direct and indirect consumption. The terms direct and indirect consumption of a product indicate, in the case of direct consumption, the direct use of the product by the customer. In other words, the product has no other purposes than those for which it was produced. (Examples: Food, clothes). On the contrary, an indirect consumption of a product means that the product has been produced to be used for another purpose (Examples: Laboratory equipment, packaging).

Long life time. It is considered that a life span is long when it exceeds one year. Food or drinks, for example, do not fall into this category.

Maintenance. A product needs maintenance when an expert must visit the product to check its proper operation. Thus, the product is constantly monitored until the end of its life cycle. (Examples: Mechanical lifts, cars).

Remote modification. A modification is considered remote when a company can make it on a product from its offices, without requiring the intervention of an expert. (Examples: Websites or Software).

The products of each cluster and their characteristics are detailed in Table 3.

Table 3. Main characteristics of the Clusters.

Cluster characteristics	Textile	Equipment manufacturing	Software and technology
Direct consumption	X	-	-
Indirect consumption	-	X	X
Long life time	X	X	X
Maintenance	-	X	-
Remote Modification	-	-	X

3 The Propositions – Hypotheses and Questionnaire

3.1 The Propositions – Hypotheses

The first proposition – hypothesis (PH1) is proposed to establish the link among the presence of technologies related to the concept of Smart Manufacturing, Smart Product, Smart Working and Smart Supply Chain in a company under study, and the degree of implementation – maturity stage of the Industry 4.0 concept in this company. Indeed, all these technologies fit the concept of Industry 4.0; thus, they are essential to reach a high degree of implementation – maturity stage.

The second proposition – hypothesis (PH2) surges as the certain importance of the technologies linked to the term Smart Manufacturing. The other technologies are equally important; however, those related to the term Smart Manufacturing have a special value due to the characterization of the concept of Smart Manufacturing as the heart of Industry 4.0.

Therefore, it can be sustained the fact that a company with many technologies connected to the term Smart Manufacturing has a high degree of implementation – maturity stage of Industry 4.0.

These propositions – hypotheses have guided to establish the points of interest and in this way, to develop more concrete and clear questions, as it is depicted in Fig. 2.

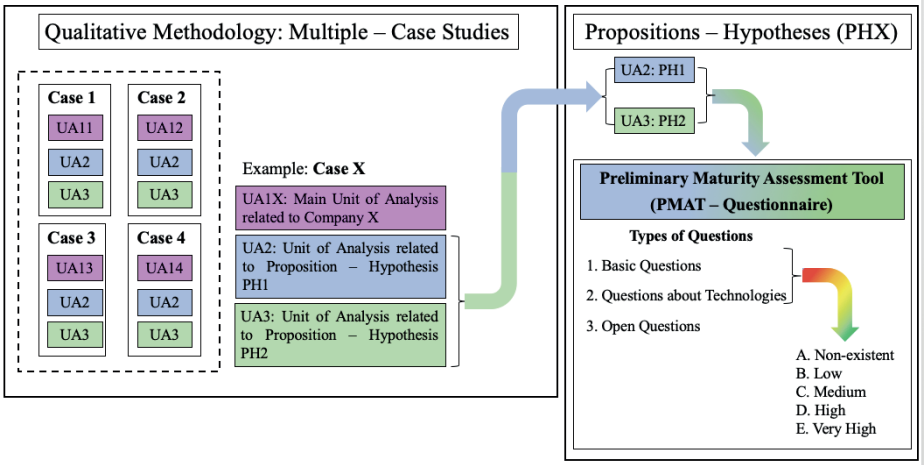

Fig. 2. The relationship between the qualitative methodology and the Preliminary Maturity Assessment Tool (PMAT – Questionnaire).

3.2 Characteristics of the Questionnaire

The objective of the questionnaire is to verify the degree of implementation – maturity stage of Industry 4.0, i.e., for each technology determine whether its implementation is basic or advanced, as well as the use of the new paradigms. Thus, most of the questions refer to estimate the degree of implementation – maturity stage of the technologies and paradigms related to Industry 4.0. Three types of questions are proposed:

- Basic questions.
- Questions about technologies.
- Open questions.

Basic questions provide information about the company, such as its name, focus, and size. These questions help to clearly define what type of company you are dealing with, whether it is large, medium or small; if it produces in series or it develops projects.

The answers make it possible to classify the different companies in a way that is then easier to take advantage of the results.

The questions that refer to technologies help to estimate their degree of implementation – maturity stage in the Industry 4.0 concept. These questions are closed and a 5-point scale has been used to specify the level – stage of knowledge of each employee regarding every technology, since this level – stage is directly related to the actual degree of implementation – maturity stage. The 5 points are as follows:

A) Non-existent.
B) Low.
C) Medium.
D) High.
E) Very High.

Some questions asked whether the company had particular computer systems or it had the previous versions of these systems.

On the other hand, other questions referred to if the employees thought if a technology was feasible (to be able to verify its implementation in the company in another way). Thus, several different questions were available, although they focused only on technologies.

At the end of the questionnaire, the open questions appeared with the objective of explaining the differences in the degree of implementation – maturity stage of different technologies:

- One of these questions concerned measures taken in the past to achieve compliance with the principles of Industry 4.0. The completed responses helped to understand the current situation of the company, and thus, it was possible to verify if these measures were efficient.
- The other one refers to the belief in the efficiency of Industry 4.0 and the need to trace the production system to it. This question was necessary since it indicated the opinion of the employees on this matter, an opinion that is revealed to be important since the employees are who allow the good functioning of the company, and if they do not believe in Industry 4.0, they cannot adapt to use it.

The following section analyzes the responses of the companies and shows if the established clusters are related to each other through common characteristics.

4 Analysis of Results

4.1 Closed Questions

Table 5 represents the implementation of advanced technologies in Industry 4.0 through the use of colors whose meanings are coded in Table 4.

The companies are divided into the clusters chosen above and the results were averaged for each company.

Table 4. Meaning of the color coding.

Meaning	Colors
High implementation	
Medium implementation	
Low implementation	
No implementation	
Not known	

It has been chosen to use colors to describe the degree of implementation – maturity stage of the technologies, so that the differences among the clusters are more visible.

Table 5. Results of the closed questions (Types 1 and 2).

Cluster			Textile	Software and technologies	Equipment manufacturing
Smart Manufacturing	Vertical integration	Sensors and Actuators			
		ERP			
		MES			
		SCADA			
	Virtualization	3D Representation			
		Artificial Intelligence			
	Autonomous robots	Robots along the production chain			
		Communication networks among them			
	Traceability of products				
	Flexibility	3D Printing			
		Adaptation of production lines			
		Monitoring about energy consumption			
Smart Working	Remote control of production				
	Augmented reality	Augmented reality during manufacturing			
		Augmented reality during training of workers			
Smart Supply Chain	Digital platforms company-clients-suppliers				
	Digital platforms among companies				
Smart Product	Interconnectivity of products				
	Supervision and control of final products				
	Data return				
Cybersecurity					

Table 5 shows that the cluster related to the textile sector fits globally with the principles of Industry 4.0. Indeed, with the exception of 3D printing, all advanced technologies are implemented and particularly those that relate to the term Smart Manufacturing, a fact that, according to the propositions – hypotheses previously described, shows a high degree of implementation – maturity stage of Industry 4.0.

The cluster related to Software and Technologies companies presents a medium degree of implementation – maturity stage of Industry 4.0, due to the diversity of degree of implementation – maturity stage of each technology. This grade is high for some technologies contained in Smart Manufacturing and low for others. Therefore, this cluster can be assimilated to an intermediate cluster respecting the principles of Industry 4.0.

The cluster that includes Equipment Manufacturing companies shows a low degree of implementation – maturity stage of Industry 4.0. Indeed, very few current technologies are known in these companies, with the exception of the technology that refers to the rapid adaptation of production lines.

Thus, the three clusters describe three implementation states of Industry 4.0 in the region under study: high, medium and low. In this way, it was possible to validate the choice made previously about the distribution of the companies in the three clusters and to analyze the reasons for the differences among them, thanks to the open questions that were proposed in the questionnaire.

From now on, it is called Cluster 1, the cluster associated to the Textile sector; Cluster 2, the one related to Software and Technologies, and Cluster 3, the one linked to Equipment Manufacturing.

4.2 Open Questions

The question related to the measures taken in the past regarding the integration of the principles of Industry 4.0 indicates that Clusters 1 and 2 took many measures with the aim of integrating these principles, unlike Cluster 3, which did not take any measure.

The question that refers to the opinion of the company regarding the need for Industry 4.0 shows a lack of knowledge of the companies in the Cluster 3. Indeed, the companies do not seem to know about the existence of this Industry, but they seem inclined to be interested to this concept. On the other hand, Clusters 1 and 2 are both convinced of the importance of matching it.

4.3 Analysis of the Results Based on the Characteristics Studied

According to the results obtained, it can be seen that the two characteristics of the final products of a company that induce a high degree of implementation – maturity stage of Industry 4.0 are direct consumption combined with a long-life span. These two characteristics are those of the products produced by the companies of the Cluster 1 and caused industrial needs that resulted in an efficient implementation of the advanced technologies of Industry 4.0.

On the other hand, it was found that indirect consumption induces a good degree of implementation – maturity stage, only if it is combined with a possibility of remote modification (Cluster 2) and not with a need for maintenance (Cluster 3).

These conclusions are clear, but one should be cautious about their implications, due to the limits of the study that are described as follows.

4.4 Limits of the Study

The number of companies that answered the questionnaire is the main limit of this study. For the study to be more precise, more responses should have been received, therefore, a better description of the situation could have been guaranteed, adapting or even generating other clusters with other characteristics.

In addition, it has been considered throughout the study that all the technologies of Industry 4.0 were adaptable to each company and all of them were important, whatever the industrial sector. However, there are sectors that do not need certain technologies because they are incompatible with the way companies operate.

For instance, a software company does not need 3D printing to produce its services. Thus, this technology is not going to be raised or considered by the directors of this company, and the absence of this technology does not mean that the company is lacking a way to square with Industry 4.0.

5 Discussion

5.1 Comparative Analysis

This section proposes a comparative analysis by considering different *maturity models* of Industry 4.0.

Mittal et al. [14] propose a critical comprehensive review of smart manufacturing and Industry 4.0 *maturity models*, and their implications for small and medium-sized enterprises (SMEs), by analyzing their fit and recognizing the specific requirements of SMEs. This work presents features that are characteristic for SMEs and identify research gaps needed to be addressed to successfully support manufacturing SMEs in their progress towards Industry 4.0.

The work of [14] develops an exhaustive analysis by comparing different methodologies, such as *framework*, *maturity model*, *readiness assessment*, and *gap analysis*, which are used to discuss the enterprise journey towards smart manufacturing (SM) and Industry 4.0.

An important observation from the study of [14] is that researchers have different perspectives towards the understanding of *dimensions* ([15], [16], [17], [18], [19]). For instance, Schuh et al. [15] mentioned resources, information systems, organization structure and organization culture as the *dimensions*. While Schumacher et al. [18] noted strategy, leadership, culture, people, and governance.

Moreover, Mittal et al. [14] indicate that only [20] and [21] mentioned the prerequisites of Industry 4.0 in the form of technologies, toolbox and building blocks. In this group, the work of Frank et al. [12] can be included.

Frank et al. [12] propose a structure of Industry 4.0 technology layers that shows levels of adoption of these technologies and their consequences for the implementation of the Industry 4.0 concept. This structure is synthetized as a *final framework* which represents a *maturity pattern* of the Industry 4.0 implementation. This framework of Industry 4.0 technologies suggests two *layers of adoption*: 1) front-end technologies, and 2) base technologies.

The first layer includes four *dimensions* of Industry 4.0: Smart Manufacturing, Smart Products, Smart Supply Chain and Smart Working. The second layer considers technologies that provide connectivity and intelligence to the front-end technologies. In order to understand the connections among the technologies, as well as to define patterns of adoption of the two layers, a cluster analysis in relation to the companies under study is applied.

According to Schuh et al. [15], the Acatech Industrie 4.0 Maturity Index divides the structure of a company into four structural areas or *dimensions* (Industry 4.0 capabilities): 1. Resources 2. Information systems 3. Organizational structure 4. Culture. Each dimension is defined by two principles that are identified along with the capabilities required for each structural area. The capabilities are geared towards the achievement of the various stages of development and provide manufacturing companies with the foundation to transform into agile organizations. The Acatech Industrie 4.0 Maturity Index has six *maturity stages*: 1. Computerization 2. Connectivity 3. Visibility 4. Transparency 5. Predictive capability 6. Adaptability.

Schumacher et al. [18] propose five *maturity stages*: Likert-scale reaching from 1 (not distinct) to 5 (very distinct). Nine company *dimensions*: 1. Strategy; 2. Leadership; 3. Customers; 4. Products; 5. Operations; 6. Culture; 7. People; 8. Governance; 9. Technology.

Leyh et al. [22] describe the model called SIMMI 4.0, which has five *maturity stages*: 1. Basic digitization level. 2. Cross-departmental digitization. 3. Horizontal and vertical digitization. 4. Full digitization 5. Optimized full digitization. The model SIMMI 4.0 includes four *dimensions*: 1. Vertical integration. 2. Horizontal integration. 3. Digital product development. 4. Cross-sectional technology criteria.

Lichtblau et at. [23] present an Industry 4.0 *maturity model* (IMPULS) which consists of six *stages*: 0. Outsider. 1. Beginner. 2. Intermediate. 3. Experienced. 4. Expert. 5. Top performer. Moreover, [23] depict six *dimensions* which are further (detailed into 18 fields): 1. Strategy and organization. 2. Smart factory. 3. Smart operations. 4. Smart products. 5. Data-driven services. 6. Employees.

Colli et al. [24] propose a digital *maturity model* which takes into consideration a number of existing digital *maturity models* ([15], [18], [22], [23]).

This maturity model of Colli et al. [24], it is suggested to assess the level of digitization of an organization, and it is composed by six sequential digital *maturity stages*: None, Basic, Transparent, Aware, Autonomous, Integrated.

In order to map the digital capabilities of the organization, these stages are grouped into five areas which are called digital *dimensions*: Governance, Technology, Connectivity, Value creation, Competences.

As an extension of [24], Colli et al. [25] present a contribution that consists of raising the need for contextualization in relation to digital maturity assessments by proposing a novel assessment approach to address this need.

In addition, [25] provide a reference model which is based on the Acatech maturity model [15], chosen for its focus on data and connectivity, which relates *maturity stages* and *dimensions* for mapping the information collected during the assessment process, as well as a more detailed description of the proposed assessment procedure, testing it in three cases and discussing its contextualization capabilities and the key contextual

factors that emerged. The proposed approach is intended as a learning tool, based on PBL (Problem Based Learning), to assist professionals in providing company-specific guidelines as a result of a digital *maturity assessment*, and academics in their study of the transition through *digital maturity stages* in many contexts.

Finally, this work has proposed the development of a Preliminary Maturity Assessment Tool (PMAT) which is used to identify technologies related to Industry 4.0, and to verify their *degree of implementation – maturity stages* in companies from different sectors.

The PMAT is based on two propositions – hypotheses which are connected to two *dimensions* of Industry 4.0, related to front-end-technologies: 1. Smart Manufacturing. 2. Smart Products. 3. Smart Supply Chain. 4. Smart Working.

The PMAT consists of a Questionnaire with three types of questions. The first and second types include a 5-point scale: 1. Non-existent. 2. Low. 3. Medium. 4. High. 5. Very High. This scale indicates five *degree of implementation – maturity stages.*

5.2 Possible Future Work

A possible future work could be an improvement of the PMAT, i.e. the SMART (Skilled–Maturity Assessment Research Tool) by means of increasing the propositions – hypotheses, thus, to achieve an enrichment of the number of *dimensions* related to Industry 4.0 front-end-technologies, as well as their base technologies.

Moreover, the SMART with an improved Questionnaire with other types of questions could be proposed. Therefore, a discussion with each company could be established with the aim of adapting the questions to the language of the company and the type of products it provides so that employees can answer the questions more precisely and exhaustively. In order to indicate five *degree of implementation – maturity stages*, the 5-point scale (1. Non-existent. 2. Low. 3. Medium. 4. High. 5. Very High) could also be included.

Finally, in a new study it is possible to investigate in depth, what are the current patterns of adoption of technologies related to Industry 4.0 that are implemented in the companies of the region under study.

6 Conclusions

This work developed a Preliminary Maturity Assessment Tool (PMAT). The PMAT founds on two propositions – hypotheses and consists of a questionnaire that is based on three types of questions, where the two first types include a 5-point scale.

The PMAT is used to identify technologies related to Industry 4.0, as well as to verify their degree of implementation – maturity stages in companies from different sectors.

What stands out from this study is the willingness of companies to adopt Industry 4.0 as a production paradigm. Even companies that did not know the term or the concept showed willingness to take an interest in the matter and adopt it in the near future.

The proposed questionnaire (PMAT) made it possible to investigate the degree of implementation - maturity stages of the technologies involved in different companies, and in this way, to have a point of reference on the current state of knowledge and the measures adopted by the companies.

Therefore, this first study was very encouraging for future research projects related to the patterns of implementation of Industry 4.0 technologies in companies in the region under study.

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Evidências da Indústria 4.0 no setor eletroeletrônico basileiro: um estudo multicasos a partir da literatura

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Resumo. Com a crescente evolução industrial e tecnológica, o setor produtivo está passando por mudanças profundas em sua estrutura e operações, o que está sendo entendido como a Quarta Revolução Industrial, ou Indústria 4.0 (I4.0). Este termo retrata a digitalização e a interoperabilidade no setor industrial global, despertando interesses nos setores público e privado. O presente trabalho caracteriza este paradigma industrial abordando seus conceitos, princípios e pilares tecnológicos para, posteriormente, realizar um estudo multicasos, discutindo usos de tecnologias relacionadas à I4.0 no setor eletroeletrônico brasileiro, com objetivo de retratar os avanços das organizações brasileiras neste contexto. Realizou-se uma revisão sistemática da literatura, construindo dois portfólios bibliográficos: um para a etapa teórica, de caracterização; e outro para a etapa de casos. Em seguida, realizou-se análise bibliométrica e análise de conteúdo dos documentos do portfólio teórico, de modo a identificar as categorias de análise pertinentes à realização da etapa subsequente, de estudo de casos múltiplos. Essa etapa envolveu a análise de cinco casos selecionados, apresentando aplicações de tecnologias da I4.0 nas áreas de fabricação de máquinas, operação e monitoramento de usinas hidrelétricas, educação e regulação do setor elétrico. A partir deste estudo, pode-se compreender "como" e "em quê" os benefícios e tecnologias da I4.0 são utilizados em diferentes aplicações ou segmentos industriais do setor eletroeletrônico. Os aspectos presentes de forma predominante em todos os casos foram os princípios de intercoexão e virtualização; os benefícios de flexibilidade e integração das informações; e as tecnologias IIoT e computação em nuvem. Pesquisas futuras poderão utilizar a mesma estrutura teórica para conduzir estudos de casos empíricos, retrospectivos ou longitudinais, sobre a migração, adoção, uso ou desenvolvimento de tecnologias da I4.0 em contextos específicos, visando retratar a situação real das empresas e organizações sobre "o quê" e "como" utilizam ou se inserem no conceito de I4.0.

Palavras-chaves: Indústria 4.0, manufatura avançada, setor eletroeletrônico, estudo multicasos.

1 Introdução

A Indústria 4.0, ou I4.0, é caracterizada pelo aprimoramento das tecnologias da Terceira Revolução Industrial e da disseminação de inovações tecnológicas incorporadas no chão-de-fábrica, virtualizando a automação ao longo da cadeia de produção e permitindo a fusão do mundo físico ao digital [1].

Esta nova revolução industrial "transformará a fabricação, operação, *design* e serviço de produtos e sistemas de produção", por meio da "conectividade e interação entre peças, máquinas e seres humanos", elevando a eficiência dos sistemas de produção em 25% e acelerando a produtividade em 30% [2]. Máquinas e sistemas se comunicarão entre si por sistemas ciber-físicos (CPS - *Cyber-Physical Systems*) através da Internet das Coisas (IoT - *Internet of Things*), operando a produção de forma autônoma e auxiliando o ser humano, simultaneamente.

Conforme indica [3], o setor industrial brasileiro é o 9º maior do mundo, representando, atualmente, cerca de 10% do PIB nacional, valor três vezes menor ao que representava na década de 80. O Brasil está na 41ª posição em estrutura de produção e na 47ª posição nos vetores de produção da indústria internacional. O país possui potencial para melhorar sua situação na nova economia, investindo na integração de tecnologias emergentes e capacitação em áreas da engenharia, integração de sistemas, comunicação digital, análise de dados e trabalho multidisciplinar, entre outras.

Assim, este trabalho visa caracterizar a I4.0, definindo as principais tecnologias que compõem esse novo padrão industrial, bem como apontando e descrevendo aplicações de tais tecnologias no âmbito industrial eletroeletrônico brasileiro.

Pelo fato da Indústria 4.0 já estar sendo desenvolvida e aplicada especialmente em países como Estados Unidos e Alemanha, se vê a necessidade de compreender esta nova revolução, para que países emergentes, como o Brasil, se aprofundem no assunto tanto no contexto acadêmico quanto, a partir disso, no setor industrial.

Dessa forma, pretende-se contribuir com a literatura discutindo conceitos, características e tecnologias da I4.0 através de uma Revisão Sistemática de Literatura (RSL); com a prática industrial brasileira e de outros países emergentes, a partir da análise de casos brasileiros de migração para a I4.0; e também com o setor eletroeletrônico brasileiro, estabelecendo alguns marcos para a adoção das práticas e tecnologias da nova revolução industrial.

2 A Indústria 4.0 e seus princípios básicos

A Indústria 4.0 surgiu nos últimos anos para retratar a digitalização e a interoperabilidade no setor industrial global [4]. O termo Indústria 4.0 (I4.0) é relacionado à Quarta Revolução Industrial, e foi utilizado pela primeira vez na Feira de Hannover em 2011, na Alemanha, a partir das iniciativas dos setores governamentais, acadêmicos e privados, para denominar uma iniciativa do governo alemão que visa o fortalecimento do poder competitivo do país na área da manufatura, através da implantação de fábricas inteligentes [5].

Nessa nova transformação industrial, máquinas, sensores e sistemas de TI se interconectam ao longo do chão de fábrica das indústrias [2]. Todos esses sistemas interagem através de protocolos baseados na internet, fazendo leituras e análises de dados

em tempo real, se adaptando a mudanças e prognosticando falhas, convertendo indústrias convencionais em fábricas inteligentes, conforme indica [6].

[1] e [7] apontam os princípios básicos para uma implantação eficaz da I4.0.

2.1 Interconexão. A interconexão, também nominada como interoperabilidade, é relacionada à troca e compartilhamento de informações entre sistemas de uma organização inteligente [8]. Tem como característica o intercâmbio de dados e acesso a sistemas por meio de uma rede industrial, fornecendo três tipos de conexões: homem-homem, homem-máquina e máquina-máquina, através da Internet das Coisas (IoT).

2.2 Virtualização (ou transparência informal). A partir da interconexão de pessoas e dispositivos, os sistemas organizacionais são capazes de criar um modelo virtual do ambiente real através de dados de dispositivos e sensores pertencentes ao mundo físico, fazendo uma cópia do mundo físico no ambiente digital [8].

2.3 Decisões descentralizadas. Com a maior automatização e individualização da produção, a dificuldade em manter um sistema de controle centralizado aumenta. Na I4.0, a descentralização se torna uma solução para descomplexificar tais problemas [1]. As decisões descentralizadas se baseiam na interconexão de pessoas e dispositivos inteligentes, que podem monitorar e executar tarefas com maior autonomia, capazes de tomar decisões por conta própria, permitidas pelos sistemas ciber-físicos (CPS), do que decorre uma produção eficiente e sincronizada. Em situações especiais, como no caso de conflito de metas, as decisões passam a ser delegadas a um nível superior [7] [8] [9].

2.4 Assistência Técnica. Através da interconexão e descentralização, máquinas e robôs passam a executar funções operacionais básicas e repetitivas, garantindo maior segurança e eficiência na produção. Ademais, podem atuar no suporte físico de outras tarefas envolvendo homem e máquina, interagindo, robôs e trabalhadores capacitados, para esse tipo de serviço colaborativo, de modo seguro e aceitável para ambos [7].

2.5 Capacidade de resposta em tempo real. A capacidade de resposta em tempo real tem a competência de coletar, analisar e fornecer os dados necessários para atender decisões instantaneamente. Os dados provenientes dos sistemas inteligentes são extraídos e analisados, com o intuito de ter respostas em tempo real para poder certificar que o sistema seja competente caso necessite de uma reação instantânea, por motivo de alteração de demanda ou mesmo por problemas operacionais [1] [8].

2.6 Modularidade. Na I4.0 a produção passa a possuir vários módulos, os quais podem se adequar e se ajustar de acordo com as necessidades do cliente, permitindo assim uma grande flexibilidade nos sistemas de manufatura. Esses sistemas modulares podem ser introduzidos em organizações industriais convencionais, fornecendo suas funções pela rede industrial através de protocolos padrões de comunicação [1] [8].

De forma complementar aos princípios de implantação, outro conceito central para a compreensão da I4.0 é o que se chama de Sistemas Ciber-Físicos (CPS). [10] definem os CPS como um "conjunto de sistemas nos quais sistemas naturais e feitos pelo homem (espaço físico) são fortemente integrados aos sistemas de computação, comunicação e controle (espaço cibernético)", tendo a descentralização e os processos de produção autônomos como principais colaboradores.

Os CPS são chaves para a criação de fábricas inteligentes, incluindo a constante troca de informação entre máquinas e dispositivos permitindo o controle autônomo, envolvendo sistemas, máquinas, produtos, clientes, estoques e serviços terceirizados [11].

3. Tecnologias-chaves associadas à Indústria 4.0

Há nove tecnologias emergentes que estão em evidência na transformação dos processsos de produção, sendo consideradas como os pilares da I4.0. Em linhas gerais, a fusão entre os mundos físico, digital e biológico é viabilizada através dessas tecnologias.

3.1 Internet Industrial das Coisas (IIoT). [12] e [13] definem a IoT através da conexão entre qualquer objeto físico, sistemas e pessoas por meio da internet. Quando referida especificamente às indústrias, a chamada Internet Industrial das Coisas (IIoT), incorpora softwares, sensores, objetos físicos, dispositivos, máquinas e demais "coisas" presentes nas indústrias, permitindo a comunicação, a coleta e a troca de dados através de sensores inteligentes, de modo que tais objetos podem se tornar participantes ativos dos processos de negócios. [4] [5] [14] [15] [16].

3.2 *Big Data Analytics.* O *Big Data Analytics*, ou simplesmente *Big Data*, representa o conjunto de tecnologias envolvidas na coleta, processamento e análise de grandes volumes de dados provenientes da IoT, sejam eles armazenados ou coletados em tempo real. [17] e [18] apontam suas três principais características: Volume – relacionado à quantidade de dados disponíveis, aumentando a capacidade analítica; velocidade – relacionada com a agilidade na geração dos dados; e variedade – relacionada à diversidade de dados gerados.

3.3 Computação em Nuvem. Os dados gerados por da IoT e *Big Data* são manipulados pela computação em nuvem, armazenando informações em banco de dados de alta capacidade. Essa tecnologia permite que clientes e trabalhadores tenham acesso aos dados ao mesmo tempo, possibilitando analisar o fluxo de dados em tempo real [6] [8] [11] [19], dispensando grandes investimentos em *softwares* e infraestruturas [20] [21].

3.4 Cibersegurança. Refere-se à proteção de dados de TI por meio de procedimentos que proporcionam segurança digital contra roubos ou danos de dados [22]. Esta tecnologia é essencial para as tendências da manufatura, visto que a I4.0 é fundamentada na digitalização e nos serviços baseados em dados, garantindo privacidade e segurança em todos os processos de produção [8]. As vulnerabilidades são comumente relacionadas a dispositivos virtuais que possuem conexão com os sistemas da nuvem [23] [24] [25].

3.5 Manufatura aditiva. A manufatura aditiva converte um desenho computacional 3D em um objeto real através da impressão em camadas. Esta tecnologia vem sendo utilizada atualmente na fabricação de produtos inteiros, personalizados de acordo com as exigências de cada cliente [26] [27], possuindo a vantagem de trabalhar com estoques reduzidos, barateando a produção e diminuindo o tempo de espera de um produto [2].

3.6 Realidade Aumentada. A realidade aumentada (RA) aprimora a visualização do ambiente físico industrial, sobrepondo em tempo real informações virtuais à realidade, gerando funcionalidades inteligentes de fabricação [2] [6], elevando os padrões da manufatura através da inserção de sons, gráficos, imagens em 3D e feedback de toque ao mundo real [6]. [28] aponta aplicações de RA nas indústrias em termos de operações,

manutenção e assistência remota, treinamento, controle de qualidade, gerenciamento de segurança, design e visualização, e logística.

3.7 Simulação. A simulação é uma tecnologia utilizada para prever comportamentos de um sistema real, utilizando modelos físicos ou matemáticos para criar e projetar sistemas reais ou ilusórios. Nos processos de produção da I4.0, a aplicação da simulação atua na redução de falhas, agilizando a tomada de decisões e reduzindo o tempo de inatividade de máquinas e dispositivos [2], rumo a retratar o mundo físico em um modelo digital, incluindo máquinas, seres humanos e produtos [2] [29]. A realização de testes virtuais de diversas configurações de procedimentos, permitirá previsões, melhorias ou alterações nos processos já utilizados [29] [30].

3.8 Robôs Autônomos. A implantação de robôs no chão de fábrica permitiu a realização de atividades que não podiam ser resolvidas facilmente pelo homem. Com a I4.0, os robôs se tornam mais flexíveis e autônomos, interagindo entre si, cooperando e aprendendo com humanos. Eles incorporarão novas capacidades, automatizando a linha de produção por conta própria e dispensando supervisionamento, coordenando ações e tarefas que são inseguras ou desagradáveis para os operários [2] [6] [31]. Os *Cobots*, ou robôs colaborativos, são pensados para trabalho cooperativo em espaço compartilhado com humanos, garantindo a segurança necessária [32].

3.9 Sistemas de Integração Horizontal e Vertical. Na I4.0, as indústrias se associarão com os recursos e funções variadas devido à integração de dados e dispositivos (CPS) com o chão de fábrica, proporcionando uma cadeia de valores realmente automatizada [2] [4]. A integração horizontal digitaliza toda a linha de processos industriais, realizando o intercâmbio de informações em toda a cadeia de valor com clientes e fornecedores, integrando diversos sistemas, recursos e processos dentro das fábricas como também com outras fábricas. Por outro lado, a integração vertical relaciona a integração de tais elementos presentes nas fábricas em diferentes níveis hierárquicos internos de produção, desde o chão de fábrica até os executivos e diretores [2] [33].

4 Metodologia

Este trabalho adotou por método a pesquisa bibliográfica, desenvolvida na forma de uma Revisão Sistemática de Literatura (RSL) [34], seguida por um estudo multicasos [35].

A pesquisa bibliográfica consistiu na análise de artigos científicos publicados em periódicos indexados ou conferências, relatórios organizacionais e acervo legal ou regulatório nacional. Uma RSL foi realizada para a seleção das bibliografias, passando pela seleção de portfólio e realização das análises bibliométrica e de conteúdo, enfocando as tecnologias no âmbito da Indústria 4.0. Foi definido um portfolio bibliográfico teórico, sobre aspectos da I4.0; e, na sequência, outro portfolio de artigos abordando aplicações de tecnologias emergens no setor eletroeletrônico brasileiro. As etapas da pesquisa seguiram a estrutura detalhada a seguir.

Etapa 1: Planejamento da Pesquisa. A primeira etapa do trabalho consistiu em uma busca horizontal da literatura, com o objetivo de levantar informações e questionamentos para um melhor alinhamento de ideias, como também para delimitar a pesquisa e orientar seu design metodológico. Nesta busca, foram acessados artigos de periódicos

e congressos internacionais, dissertações e teses, *sites* da instituições industriais e governamentais, e relatórios institucionais.

Etapa 2: Seleção de Portfólio Bibliográfico Teórico e de Casos. Para a seleção do portfolio teórico procedeu-se a partir dos seguintes passos:

a) Escolha das bases de busca, elegendo-se as bases *Scopus, Web of Science* e *IEEEXplore*, por conterem vasto acervo de documentos e serem as principais no ramo do conhecimento cie*ntífico.*

b) Definição dos eixos de pesquisa e palavras-chaves, adotando-se os eixos e palavras-chaves conforme exposto na Tabela 1

Tabela 1. Eixos e palavras-chaves empregados na pesquisa

Eixo 1 – I4.0	Eixo 2 – Tecnologias
Industry 4.0	Cyberphysical System
Factory 4.0	Big Data Analytics
Company 4.0	Augmented Reality
Enterprise 4.0	Additive Manufacturing
Advanced Manufacturing	Cloud
	Cybersecurity
	Industrial Internet of Things
	Horizontal / Vertical System Integration
	Simulation
	Autonomous Robots

c) Coleta de dados para compor o portfólio. Aassociações de palavras-chaves foram feitas utilizando operadores booleanos, gerando 50 combinações que foram inseridas nas bases de busca, aplicando-se um filtro para retornar artigos apenas no período de 2011 a 2019. Os artigos selecionados foram importados para gerenciamento e catalogação bibliográfica por software, para melhor manipulação e seleção dos artigos.

d) Exclusão de duplicados e filtragem. A importação resultou num total de 14.941 artigos. A partir disso, foram feitas filtragens seguindo critérios baseados nos objetivos da pesquisa, começando pela eliminação de duplicações, restando 9.934 artigos. Em seguida, foram lidos os títulos (ficam 1.494 documentos), seguido dos resumos (reduz para 118). Então, se fez uma leitura preliminar de cada artigo, restando 21 referências.

e) Processo de repescagem e definição do portfólio teórico final. Após o processo de leitura preliminar, fez-se um levantamento para verificar a ocorrência de outros trabalhos dos autores dos 21 artigos dentre os descartados na etapa de leitura dos resumos. Na identificação dessas ocorrências, a mesma entraria para uma lista de repescagem. Para avaliar qual referência da lista de repescagem poderia ser reintegrada ao portfólio, se fez a leitura na íntegra dos trabalhos, para certificar o alinhamento do conteúdo às ideias e objetivos estabelecidos. Com isso, 2 referências foram resgatadas. As 23 referências totais foram lidas integralmente para avaliar se estavam seguindo o critério da pesquisa, resultando em um portfólio teórico final de 18 documentos.

Na seleção de artigos para compor o portfólio de casos, fez-se uma nova pesquisa com os mesmos procedimentos expressos nos itens de *a)* a *d)* anteriores, adicionando dois novos eixos de pesquisa: Setor Eletroeletrônico e Brasil. Também fora adicionada

a base de busca brasileira, SciELO, para garantir uma melhor aderência à pesquisa de casos brasileiros. A palavra-chave *Simulation* foi retirada nesta etapa de busca referir-se a uma gama de aplicação muito ampla em comparação aos objetivos da pesquisa, desvirtuando os resultados.

A consulta às bases com os eixos e palavras-chaves definidos resultou em 2.094 referências, tendo a base IEEEXplore 74,7% de representatividade. Após as etapas de filtragem, obteve-se o total de 13 artigos, que foram lidos integralmente. Após a leitura completa, dentre os 13 artigos, 5 atendiam aos requisitos da pesquisa da etapa de seleção dos casos, a saber: pertencer ao setor eletroeletrônico brasileiro; e utilizar tecnologias referentes à Indústria 4.0. Estes 5 artigos foram selecionados para compor o portfólio de casos, tornando possível o desenvolvimento do estudo multicasos.

Etapa 3: Análise Bibliométrica e de conteúdo do Portfólio Teórico. Esta etapa investiga a composição do conhecimento científico relacionado com o tema em questão, através de um conjunto de métodos para avaliar a relevância do conteúdo da pesquisa, verificando o alinhamento com seus objetivos [36] [37].

A análise bibliométrica indicou através de gráficos e tabelas, dados quantitativos do portfólio teórico. Os indicadores utilizados nesta análise foram: o reconhecimento científico dos artigos (citações), a relevância de autores no portfolio, a relevância dos veículos de publicação; e incidência de palavras-chaves, cujos resultados estão expostos na seção 5. Neste processo foi utilizado o *Google Scholar* para verificar quantas citações possuía cada artigo até a consulta, datada em 14 de abril de 2019.

Posteriormente, a análise de conteúdo foi centrada na extração e vinculação de informações relevantes do portfolio de casos, adotando-se as seguintes categorias *a priori* de análise, todas relativas à I4.0: princípios de implantação; benefícios percebidos ou esperados; principais tecnologias.

Etapa 4: Estudo Multicasos. A etapa do estudo multicasos adota abordagem qualitativa, enfocando a ampliação de conhecimento do tema I4.0 no setor eletroeletrônico brasileiro. A escolha pelo estudo de casos múltiplos visa a comparação entre os casos, investigando semelhanças, distinções e correlações entre eles, corroborando com a pesquisa e seus métodos aqui empregados [35].

Para a seleção dos casos, utilizou-se como critério de filtragem o enfoque descritivo acerca dos elementos abordados nas seções 2 e 3 deste trabalho: os princípios de implantação da I4.0, seus benefícios e as tecnologias consideradas como pilares. Tais elementos são resgatados da análise de conteúdo do portfolio teórico.

Na análise dos 5 casos selecionados, descritos como A, B, C, D e E, são detalhadas aplicações de tecnologias 4.0 em diferentes segmentos ou finalidade específicas do setor eletroeletrônico brasileiro, permitindo acompanhar iniciativas da revolução 4.0 em diversas áreas deste setor no Brasil.

5 Portfólio teórico, análise bibliométrica e análise de conteúdo

A presente seção apresenta os resultados da seleção do portfólio teórico, bem como sua análise bibliométrica e de conteúdo.

A Tabela 2 apresenta o portfólio teórico selecionado, relacionando o número de citações dos artigos. Este levantamento serve para visualizar, em um contexto geral, o nível de reconhecimento científico de cada artigo.

Tabela 2. Identificação e citações do portfolio teórico

Código	Ref.	Autores, ano e título do artigo	Citações
A4	[7]	HERMANN; PENTEK; OTTO (2016). *The industrial internet of things (IIoT): An analysis framework*	1054
A6	[5]	KANG *et al*. (2016). *Smart manufacturing: Past research, present findings, and future directions*	273
A18	[9]	ZHONG *et al*. (2017). *Intelligent manufacturing in the context of industry 4.0: a review*	161
A14	[32]	THOBEN; WIESNER; WUEST (2017). *"Industrie 4.0" and smart manufacturing: a review of research issues and application examples*	137
A15	[31]	VAIDYA; AMBAD; BHOSLE (2018). *Industry 4.0: a glimpse*	63
A11	[4]	PEREIRA; ROMERO (2017). *A review of the meanings and the implications of the Industry 4.0 concept*	36
A17	[18]	XU; DUAN (2019). *Big data for CPS in industry 4.0: a survey*	30
A13	[16]	SISINNI *et al.* (2018). *Industrial internet of things: challenges, opportunities, and directions*	29
A8	[8]	MITTAL *et al*. (2017). *Smart manufacturing: characteristics, technologies and enabling factors*	29
A12	[29]	RODIČ (2017). *I4.0 and the new simulation modelling paradigm*	20
A1	[15]	BOYES *et al*. (2018). *The industrial internet of things (IIoT): an analysis framework*	18
A3	[11]	FATORACHIAN; KAZEMI (2018). *A critical investigation of I4.0 in manufacturing: theoretical operationalisation framework*	12
A10	[6]	OZTEMEL; GURSEV (2018). *Literature review of Industry 4.0 and related technologies*	9
A2	[30]	CEMERNEK; GURSCH; KERN (2017). *Big data as a promoter of industry 4.0: lessons of the semiconductor industry*	4
A9	[38]	NAVICKAS; KUZNETSOVA; GRUZAUSKAS (2017). *Cyber–physical systems expression in industry 4.0 context*	3
A7	[39]	LEZZI; LAZOI; CORALLO (2018). *Cybersecurity for Industry 4.0 in the current literature: a reference framework*	1
A16	[40]	VIEIRA *et al*. (2018). Setting an industry 4.0 research and development agenda for simulation: a literature review	1
A5	[12]	JIANG *et al.* (2018). Cyber physics system: a review	0

5.1 Análise Bibliométrica. Quatro análises foram conduzidas nesta etapa da pesquisa. Fez-se o levantamento de reconhecimento científico dos artigos, por meio do número de citações dos documentos pertencentes ao portfólio teórico; e análise de relevância dos autores e dos veículos de publicação no tema. Por fim, apresenta-se uma bibliometria de incidência de palavras-chaves nos artigos do portfolio.

No que se refere à relevância científica dos artigos, o maior destaque é o trabalho A4 [7], apresentando 1054 citações. Deve ser considerando, no entanto, que este trabalho data de 2016, dispondo de mais tempo para ser citado do que maioria dos demais o que, num tema emeregente como I4.0, é relevante. Juntos, os artigos A4, A6, A14 e A18 correspondem a 86,4% do total de citações do portfólio teórico, constituindo-se em base importante para as futuras discussões qualitativas.

No que concerne à recorrência de autores, verifica-se que apenas um autor dentre os 62 existentes assina mais de um artigo incluso no portfólio, o que sinaliza na direção de que ainda não há uma concentração de pesquisa sobre o tema. Já no que tange à relevância dos veículos de publicação, embora o periódico Procedia Manufacturing seja o único com 2 artigos no portfolio, a diferença é muito sutil frente aos demais, com um artigo. Dado que o tema é emergente, a dinâmica desse indicador tente a ser grande.

Por fim, o resultado do levantamento da incidência das palavras-chaves dos artigos do portfólio é mostrado na Figura 1.

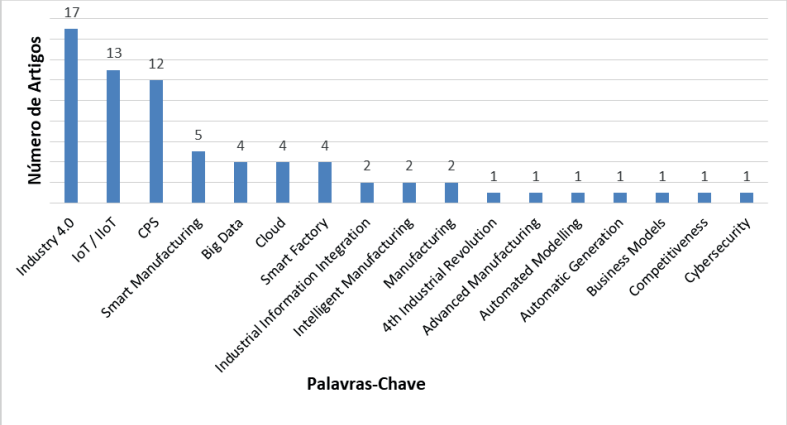

Fig. 1. Ocorrência de palavras-chaves no portfolio teórico

5.2 Análise de Conteúdo. A análise de conteúdo aqui apresentada descreve os conteúdos provenientes dos documentos do portfólio teórico utilizados para a elaboração das seções 2 e 3 deste trabalho. Essa análise auxilia na reinterpretação do que já fora abordado, oferecendo ao leitor uma compreensão mais acessível dos conteúdos em um nível superior se comparado com uma simples leitura [41].

Para facilitar a compreensão, as informações dos documentos do portfólio teórico foram reunidas em dois quadros para melhor visualização e comparação das informações de cada elemento, como pode ser visto na Tabela 3 e Tabela 4. Estas tabelas são utilizadas posteriormente para comparar os casos de estudo, confrontando os relatos de casos empíricos às informações provenientes da literatura teórica.

Tabela 3. Análise de conteúdo sobre os princípios e benefícios da I 4.0

Dimensão	Elemento	Descrição	Códigos
Princípios	Interconexão	Conexão entre sistemas industriais, com troca e processamento de informações	A3, A4, A8, A13
	Virtualização / Transparência Informacional	Criação de um modelo virtual da situação real a partir de dados, permitindo monitoramento e tomada de decisão em sistemas	A4, A8
	Decisões Descentralizadas	Capacidade dos sistemas tomarem decisões sozinhos através da interconexão, executando trabalhos com mais autonomia	A4, A8
	Assistência Técnica	Assistência ao homem em diversas tarefas pelos sistemas	A4, A10
	Cap. de resposta em Tempo Real	Agilidade dos sistemas em coletar e conceder decisões instantaneamente	A8
	Modularidade	Alta flexibilidade na alteração repentina de tarefas da linha de produção	A8
Benefícios	Demanda Personalizada / Customização	Capacidade de realizar alterações específicas em qualquer etapa da produção	A3, A8, A10, A11, A14, A15
	Flexibilidade Produtiva	Agilidade em atender diversas demandas customizadas, permitindo uma tomada de decisões mais inteligente e responsável	A3, A8, A10, A13, A14, A15, A18
	Info. Compart. / Integração das Operações	Aumento na eficiência através de integrações entre sistemas	A3, A4, A8, A10, A15, A18
	Produtividade de Recursos Melhorada	Gerenciamento de recursos e energia mais automatizado	A3, A8, A10, A11, A14, A15, A17

Tabela 4. Análise de conteúdo sobre as tecnologias da I 4.0

Tecnologias	Descrição	Códigos
Sistemas Ciber-Físicos	Conjunto de sistemas capaz de integrar o mundo físico com o virtual, monitorando dispositivos e máquinas	A1, A2, A3, A4, A5, A8, A10, A11, A14, A15, A17, A18
IIoT	Tecnologia capaz de conectar dispositivos e máquinas através do mesmo protocolo de internet	A1, A3, A4, A5, A8, A10, A11, A13, A14, A15, A18
Tecnologias	Descrição	Códigos

Big Data Analytics	Conjunto de tecnologias capaz de armazenar, distribuir, gerenciar e analisar grandes volumes de dados	A2, A3, A8, A10, A14, A15, A17, A18
Computação em Nuvem	Armazena os dados provenientes do *Big Data* em um servidor na internet	A3, A8, A10, A15, A17, A18
Cibersegurança	Garante segurança digital nas organizações contra ataques virtuais	A7
Manufatura Aditiva	Tecnologia que permite criar qualquer objeto através de impressões 3D	A8, A15
Realidade Aumentada	Visualização do ambiente real junto a dados e opções virtuais por dispositivos	A10, A15
Simulação	Prevê comportamentos desejados e não desejados de sistemas reais através da projeção em ambiente virtual	A10, A12, A15, A16
Robôs Autônomos	Robôs que interagem entre si, aprendendo com humanos e também uns com os outros	A10, A14, A15
Sistemas de Integração Horiz. e Vert.	Sistemas que integram toda a linha de chão de fábrica em nível horizontal, integrando elementos verticalmente em nível hierárquico	A11, A15

Na Tabela 3 pode-se notar que os benefícios da I4.0 são bastante abordados em documentos para retratar o "patamar 4.0", juntamente com as definições e características dessa nova revolução. Por outro lado, ao observar a Tabela 4, nota-se que as tecnologias mais citadas nos artigos são os CPS, IIoT, *Big Data* e Computação em nuvem, pelo fato de serem praticamente essenciais para a implantação da I4.0 nos ambientes fabris, atuando diretamente na interconexão entre dispositivos e pessoas.

6 Análise dos casos

O setor eletroeletrônico no Brasil é organizado em diversas áreas industriais, como informática, automação industrial, componentes eletrônicos, telecomunicações, geração e distribuição de energia, entre outras e está essencialmente relacionado com a I4.0, pois implementará mudanças nas empresas para se atingir o novo paradigma industrial por meio dos pilares tecnológicos, cujas tecnologias são provenientes do setor eletroeletrônico.

Na seleção de artigos para compor o portfólio de casos, fez-se nova pesquisa com a mesma metodologia do portólio de caracterização, adicionando dois novos eixos de pesquisa: Setor Eletroeletrônico e Brasil. O eixo Simulation foi retirado nesta etapa de busca por possuir uma gama de aplicação muito ampla em comparação aos objetivos da pesquisa. Nas etapas de filtragem, foram eliminados artigos duplicados e feita a leitura dos títulos e dos resumos, restando-se 13 artigos, que foram lidos na íntegra.

Após a leitura completa, dentre os 13 artigos, 5 atendiam aos requisitos da pesquisa da etapa de seleção dos casos: pertencer ao setor eletroeletrônico brasileiro e utilizar tecnologias referentes à Indústria 4.0. Estes 5 artigos foram selecionados para compor o portfólio de casos, tornando possível o desenvolvimento do estudo multicasos. São eles:

Caso A - Monitoramento em uma empresa de fabricação de máquinas [42].

Caso B - Sistema de manutenção e operação em uma usina hidrelétrica [43].

Caso C - Monitoramento de segurança de barragem em uma usina hidrelétrica [44].

Caso D - Medição sem fio do consumo de energia elétrica em uma linha de produção industrial avançada [45].

Caso E - Sistema de análise de dados para o setor elétrico brasileiro [46].

Embora tenha sido realizada análise individual dos casos, neste trabalho não é descrito esse detalhamento. Será enfocado o resultado do estudo comparativo entre os casos, por trazerem maior contribuição, de forma consolidada.

Para realizar a análise multicasos, as Tabelas 3 e 4 da seção 5.2 (análise de conteúdo) são rearranjados para confrontar os casos, resultando nas Tabelas 5 e 6, construídas a partir das informações disponíveis nos documentos de cada caso. Como leganda, adota-se a cor branca para representar que não há informações sólidas sobre o uso ou não dos elementos nos casos; a cor vermelha quando é especificado que não há uso algum de determinado elemento; a cor cinza para indicar que há pouco ou algum tipo de utilização de elementos; e a cor verde para indicar uso moderado ou expressivo dos elementos.

Tabela 5. Indicação de princípios e benefícios da I4.0

Dim.	Elemento	Caso A	Caso B	Caso C	Caso D	Caso E
Princípios	Interconexão					
	Virtualização / Transparência Info.					
	Decisões Descentralizadas				-	-
	Assistência Técnica				-	-
	Capacidade de Resposta em Tempo Real					-
	Modularidade			-		-
Benefícios	Demanda Personalizada / Customização	-	-			
	Flexibilidade Produtiva					-
	Info. Compart. / Integração das Operações					
	Produtividade de Recursos Melhorada		-			

Analisando a Tabela 5, pode-se notar o elemento Interconexão presente em todos os casos, bem como os demais elementos aplicados em quase todos, corroborando com a caracterização da Indústria 4.0, que relaciona tais elementos diretamente com suas características de implantação. O elemento Demanda Personalizada / Customização em Massa é uma exceção neste sentido, pois dentre os cinco casos abordados, apenas o Caso D indica sua aplicação, o qual apresenta uma linha de produção completa, desde o início de fabricação até a expedição.

Tabela 6. Ocorrência de aplicações das tecnologias da I4.0

Dim.	Elemento	Caso A	Caso B	Caso C	Caso D	Caso E
Tecnologias	Sistemas Ciber-Físicos	-		-	-	-
	IIoT	RFID		Protoc. XMPP	RFID	
	Big Data Analytics		-			
	Computação em Nuvem					
	Cibersegurança	-	-			-
	Manufatura Aditiva	-	-			
	Realidade Aumentada	-	-	-	*QR Code*	
	Simulação	-	-	-	*Digital Twin*	-
	Robôs Autônomos	-	-		*Cobots*	
	Sistemas de Integração Horizontal e Vertical				-	
	Outros	-	Manut Preditiva	-	-	-

Analisando a Tabela 6, fica evidente o uso da tecnologia IIoT em todos os casos, assim como o *Big Data* e Computação em Nuvem, pois estas tecnologias são essenciais para a comunicação, coleta de dados e armazenamento entre dispositivos, máquinas e pessoas, sendo o ponto principal deste novo conceito de manufatura.

O elemento Sistemas Ciber-Físicos não é citado diretamente entre os casos, porém, pode-se afirmar, indiretamente, que os dispositivos/maquinários utilizados nos casos são sistemas ciber-físicos, pois podem se comunicar, realizar trocas de dados e interagir entre si, unindo o ambiente físico ao ambiente virtual através da Internet das Coisas.

Outro destaque importante está no Caso D, que emprega diversas tecnologias e apresenta vários benefícios de I4.0 em uma linha de produção utilizada para realizar medições de consumo de energia elétrica remotamente, podendo analisar na prática o real uso de tais elementos em um ambiente fabril, sendo este o único caso de estudo que envolve I4.0 em uma linha de produção.

7 Conclusões

O presente trabalho teve por objetivo caracterizar a Indústria 4.0, bem como seus conceitos, princípios e tecnologias-chaves, buscando evidenciar, à luz da literatura, casos de uso de tecnologias 4.0 no setor eletroeletrônico brasileiro através de um estudo multicasos.

As informações oriundas da definição do portfólio bibliográfico teórico e da análise bibliométrica e de conteúdo foram importantes para posteriormente realizar a pesquisa da etapa de casos e definir o segundo portfólio do trabalho, buscando casos de estudo que envolvem os elementos abordados na análise de conteúdo.

Os casos utilizados para análise foram selecionados com base em duas premissas: pertencer ao setor eletroeletrônico brasileiro e utilizar tecnologias associadas à I4.0. Portanto, 5 casos foram selecionados, abrangendo as áreas de fabricação de máquinas,

operação e monitoramento de usinas hidrelétricas, educação e regulação do setor elétrico. Os casos foram desenvolvidos tanto por empresas privadas como órgãos públicos, concluindo que o interesse pelo tema desta pesquisa é de ambos os setores do país, privado e público.

Cada segmento industrial abordado neste estudo apresenta suas próprias aplicações e singularidades, o que enaltece a importância e versatilidade da I4.0 no futuro para garantir a competitividade de indústrias e organizações.

A pesquisa traz contribuição teórica em termos do levantamento e sistematização da literatura sobre o tema, propondo uma estrutura conceitual para análise de casos. Em termos de contribuição prática, agrupa e evidencia casos específicos de aplicação de tecnologias relacionadas à I4.0 no setor eletroeletrônico, permitindo, além de melhor conhecer a realidade desse setor na adoção dos princípios e tecnologias I4.0, comparar os benefícios percebidos por essas organizações nessas iniciativas.

Algumas limitações de pesquisa podem ser especificadas. Pelo fato do tema em questão ser muito recente, algumas abordagens não apresentavam uma teoria sólida sobre os assuntos estudados. Também por essa razão, foram encontrados poucos casos para análise, sendo alguns destes pouco detalhados em relação ao desenvolvimento do uso das tecnologias e como foram utilizadas realmente.

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Production Planning in a Seru Production System, Considering Heterogeneity to Balance Production Times and Minimize Energy Consumption

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Abstract. With the rise of Industry 4.0 an era of real-time global connectivity between customers and the processes that transform consumer goods is imminent. Faced with the need to satisfy the current dynamic demand, the Japanese technology industry has developed an innovative production system called Seru, which is distinguished by its satisfactory results in economic and environmental terms. This study poses a production planning problem in a Seru production system considering heterogeneous workers and the energy consumption of production. To solve it, a multi-objective mathematical model is proposed in order to balance the production time between workers (intra-Seru) and between serus (inter-Seru) and minimize the total energy consumption. For larger instances, a metaheuristic algorithm is developed based on the evolutionary algorithm NSGA-II. Finally, the effectiveness of the proposed genetic algorithm is evaluated by comparing the area under the curve obtained with the solutions of the pareto frontier that it generates and the area under the curve from the pareto frontier of the multi-objective linear optimization model created via ε - constraint.

Keywords: Seru Production System, Production Planning, Line Balancing, Heterogeneity, Energy Consumption, CO_2 Emissions

1 Introduction

The Seru production system (SPS) is recognized for its economic and environmental benefits (double E) [2]. Due to the growing concern about environmental problems, studies related to sustainable production systems have acquired greater relevance. However, the SPS has not been widely studied in this area. According to [2], only those companies that lead a transformation towards environmental efficiency will be competitive. On the contrary, those that do not modify their traditional production processes will incur in high costs for waste, fines for violation of environmental legislation and high costs for energy consumption.

According to a 2020 report by UNEP (United Nations Environment Program), the record for global concentrations of carbon dioxide has been reached despite the COVID-19 crisis. Through the drilling of an ice core it was determined that in the last 800,000 years the current concentration of CO_2 in the atmosphere had never been reached, 416.21 ppm. According to the World Energy Outlook in 2018 industrial activities generated 24 % of global CO_2 emissions.

Anticipating the growing need to develop manufacturing techniques to stay competitive, technology company Sony implemented SPS in 1992. Later, other companies in the technology industry such as Canon adapted this production system [4]. Both companies experienced economic and environmental benefits that have caught the attention of academics, regulators and companies [2]. Among the benefits there is a decrease in assembly time, in the number of workers required, in the space used for production, in the cost of machinery, in energy consumption and CO_2 emissions. [7]

To ensure the effective implementation of SPS. [5] proposed three problems that should be studied: 1) determine the correct moment to implement this new production system, 2) determine a suitable allocation plan of workers and products and 3) develop a practical production planning system. This study focuses on the production planning in a SPS through the assignment of workers-serus, batches-Serus and workers-tasks. The problem considers heterogeneous workers, that is, they are trained to perform a specific set of tasks. Additionally, it considers the proficiency of each worker to perform a particular task. According to[5] the aforementioned allocation problem can be associated with a traditional allocation problem with two levels, the first level being the allocation of workers to Serus and the second level being the allocation of products to Serus. These levels generate an additional worker-task assignment problem.

The characteristics of the SPS allow it to respond quickly to the fluctuating demand of Industry 4.0. This is defined as a type of manufacturing cell differentiated by two main characteristics, it is reconfigurable and includes additional operations to the production of the product such as packaging and quality processes. Its use is justified by three global advantages: increased productivity, quality and flexibility. Additionally, this system provides a *trade off* between efficiency (lean manufacturing) and responsiveness (agile manufacturing). [4].

In recent years, multiple investigations have been carried out on the Seru production system given its results in real cases of the Japanese technology industry. [2] proposed a bi-objective mathematical to minimize CO_2 emissions from production considering the energy consumption to produce a unit of a product and decrease the makespan. Additionally, they create a NSGA-II based algorithm to solve larger instances. On the other hand, [10] simultaneously addressed minimizing the total cost of production and energy consumption in an assembly line. Additionally, it considered the skills set of each of the workers to make a more efficient assignment. For small instances, they presented the mathematical formulation in order to generate an optimal pareto frontier through the ε contraint method. They also design three metaheuristic solutions using an NSGA-II, MOSA (multi-objective simulated annealing) and a PT-EC SFR

(processing time and energy consumption sorted-first rule).
Additionally, because this Japanese production system recognizes workforce as the main resource [8], researchers have shown interest in the heterogeneity of workers to carry out the allocation problem. [1] proposed a mathematical model that balances the production time between Serus (inter-Seru) and between workers (intra-Seru) considering the heterogeneity and proficiency of each worker. Using the weighted sum method, they give equal weight to both objective functions of the exact model. For larger instances they used a NSGA-II based algorithm. [11] have investigated the problem of assigning and training workers. To do this, they proposed a multi-objective mathematical model that aims to minimize the total cost composed of the cost of training and the cost of balancing the processing times of the workers of the same Seru. Additionally, they design a two-phase heuristic called the SAIG algorithm, based on the concepts of the SA (simulated annealing) metaheuristics and the IG (iterated greedy) algorithms. [12] investigated the same problem and presented the same objective functions, under a scenario where an assembly line is reconfigured into multiple Serus. To solve the assignment problems between task-worker and worker-Seru, they developed a three-stage heuristic algorithm. [13], proposed a bi-objective mathematical model that minimizes the makespan and the workload imbalance considering workers transfering between Serus. Additionally, created a NSGA-II based algorithm given the non-polynomial (NP-hard) nature of the worker assignment problem.

2 Problem Description

The production planning problem is established in a Seru production system considering heterogeneous workers. To generate a solution, the batches size must be determined for each type of product, the allocation of batches and workers to the serus and the assignment of tasks to workers according to their skills and proficiency. To carry out the assignment, it must be considered that each worker is trained to carry out a set of tasks $subS \subseteq S$. Additionally, each worker has a proficiency that determines their ability to perform a specific task. Each of the products has a deterministic demand that must be satisfied. To do so, it is possible to distribute the demand of a specific product in as many batches as serus exist, allowing a flexible allocation.

3 Mathematical formulation

3.1 Model assumptions

As assumptions of the model, we have: **1.** The demand for the products is known and deterministic. **2.** The available time of each worker is known. **3.** All products can be produced in any seru. **4.** The upper bound of workers in a seru is known. **5.** The task processing time of each product is known and deterministic. **6.** Workers can only perform tasks of their skills set. **7.** The workers' proficiency

is constant. The learning curve is not considered. **8.** workers transfer between serus is not allowed. **9.** Batch transfer between serus is not allowed. **10.** Only one worker can be assigned to perform a batch's task. **11.** Each worker of a Seru must perform at least one task from each batch assigned to the same seru. **12.** The travel time of workers between one workstation to another is negligible. **13.** The reconfiguration cost of the serus is negligible. **13.** The electrical power $[kW]$ of the machines used to perform the tasks is constant and known.

3.2 Notation

To solve small instances, the following mathematical formulation is presented. The formulation presented by [1] was taken as a basis to solve the production planning problem. They proposed a bi-objective model that aims to balance production time between workers and between serus. In the formulation presented in its model, the batches size of each type of product is known, unlike the mathematical formulation of this study where a variable is modeled to determine the batches size in order to allow a better balance of production time. Additionally, the product demand as allowed to be produced in all the available serus. Additionally, the model presented by [2] was considered to model the calculation of energy consumption depending on the machine used for each task and the time of use of this.

Sets The following sets are defined: C: set of serus $\{1, ..., n_C\}$, B: set of batches $\{1, ..., n_B\}$, S: set of tasks $\{1, ..., n_S\}$, textbf P: set of products $\{1, ..., n_P\}$, W: set of workers $\{1, ..., n_W\}$.

Parameters To model the proficiency of each worker w to perform a task s, the parameter $f_{w,s}$ is considered. Being $t_{p,s}$ the time required to carry out a task s of a type of product p in minutes, those workers with a proficiency lower than 1 finish the task in less time with respect to the standard time $t_{p,s}$. On the contrary, if the proficiency of a worker is greater than 1, it indicates that he is slower to perform the task, taking a longer time with respect to the standard time $t_{p,s}$.

To calculate the energy consumption of performing a task s of a product p by a worker w, the parameters pot_s, $t_{p,s}$ are required and $f_{w,s}$. The first parameter (pot_s) refers to the electrical power in kilowatts [kW] of the machine with which the task s is carried out. The multiplication of the standard time required to perform a task $t_{p,s}$, the proficiency of the worker who performs the task $f_{w,s}$ and the electrical power of the machine used to perform it pot_s, allows to obtain the energy consumption of performing the task s in kilowatts per minute $[kW * min]$. Additionally, the parameter ζ indicates the CO_2 emission factor $[gCO_2/kWmin]$. This allows determining the CO_2 emissions generated in production from energy consumption.

d_p, M, N, G, E are also defined. The first refers to the demand of a product p, the second and third, represent the upper bound of workers assigned to a

seru and of tasks assigned to a worker in a batch. Additionally, the parameter G represents the total available time of each worker in minutes and the parameter E is the upper bound of grams of CO_2 generated in production.

Finally, three binary parameters are defined. $x_{b,p}$ indicates whether batch b belongs to product p; $y_{p,s}$ represents if the task s is required by the product p; finally, the parameter $e_{w,s}$ indicates whether the worker w is trained to do the task s.

Decision variables The binary variable $l_{b,c}$ is defined, which indicates whether the batch b is assigned to the seru c. The binary variable $a_{w,c}$ takes the value of 1 if worker w is assigned to seru c. The binary variable $z_{w,b,s}$, represents whether the worker w performs the task s of batch b. Additionally, the binary variable ex_b indicates whether batch b is used or not in production. Finally, the variable q_b represents the batch size of b.

The proposed optimization model has two objective functions. The first objective function (FO_1) aims to balance the production times between workers and between serus. The second objective function (FO_2) aims to minimize the total energy consumption of production. The first objective function is composed of two parts: the inter-Seru balance (between Serus) and the intra-Seru balance (between workers). Equations (1) and (2) represent the variances of the production times of serus and workers, respectively. The FO_1 is formulated as the sum of these variances (3). Next, the mathematical formulation of the model is presented.

$$WO_1 = \frac{1}{C}\sum_{c=1}^{C}\left[\sum_{w=1}^{W}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S} x_{b,p}y_{p,s}e_{w,c}l_{b,c}a_{w,c}z_{w,b,s}q_b t_{p,s}f_{w,s} - \frac{1}{C}\sum_{c=1}^{C}\sum_{w=1}^{W}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S} x_{b,p}y_{p,s}e_{w,c}l_{b,c}a_{w,c}z_{w,b,s}q_b t_{p,s}f_{w,s}\right]^2 \quad (1)$$

$$WO_2 = \frac{1}{W}\sum_{W=1}^{w}\left[\sum_{c=1}^{C}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S} x_{b,p}y_{p,s}e_{w,c}l_{b,c}a_{w,c}z_{w,b,s}q_b t_{p,s}f_{w,s} - \frac{1}{W}\sum_{w=1}^{W}\sum_{c=1}^{C}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S} x_{b,p}y_{p,s}e_{w,c}l_{b,c}a_{w,c}z_{w,b,s}q_b t_{p,s}f_{w,s}\right]^2 \quad (2)$$

Minimize

$$FO_1 = WO_1 + WO_2 \quad (3)$$

$$FO_2 = \sum_{c=1}^{C}\sum_{b=1}^{B}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{w=1}^{W} x_{b,p}y_{p,s}e_{w,c}l_{b,c}a_{w,c}z_{w,b,s}q_b t_{p,s}f_{w,s}pot_s \quad (4)$$

Subject to,

$$\sum_{c=1}^{C} l_{b,c} = ex_b \quad \forall \quad b \in B \tag{5}$$

$$\sum_{c=1}^{C} a_{w,c} = 1 \quad \forall \quad w \in W \tag{6}$$

$$z_{w,b,s} \leq e_{w,s} \quad \forall \quad w \in W, b \in B, s \in S \tag{7}$$

$$\sum_{w=1}^{W} z_{w,b,s} = \sum_{p=1}^{P} x_{b,p} y_{p,s} ex_b \quad \forall \quad b \in B, s \in S \tag{8}$$

$$\sum_{c=1}^{C} a_{w,c} \leq N \quad \forall \quad c \in C \tag{9}$$

$$\sum_{s=1}^{S} z_{w,b,s} \leq M \quad \forall \quad b \in B, w \in W \tag{10}$$

$$\sum_{w=1}^{W} a_{w,c} e_{w,c} \geq \sum_{p=1}^{P} l_{b,c} x_{b,p} y_{p,s} \quad \forall \quad c \in C, s \in S, b \in B \tag{11}$$

$$z_{w,b,s} \leq \sum_{c=1}^{C} l_{b,c} a_{w,c} \quad \forall \quad w \in W, b \in B, s \in S \tag{12}$$

$$\sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} z_{w,b,s} \geq \sum_{c=1}^{C} l_{b,c} a_{w,c} \quad \forall \quad b \in B, w \in W \tag{13}$$

$$\sum_{b=1}^{B} q_b x_{b,p} \geq d_p \quad \forall \quad p \in P \tag{14}$$

$$ex_b \sum_{p=1}^{P} d_p x_{b,p} \geq q_b \quad \forall \quad b \in B \tag{15}$$

$$ex_b \leq q_b \quad \forall \quad b \in B \tag{16}$$

$$\sum_{c=1}^{C} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} e_{w,c} l_{b,c} a_{w,c} z_{w,b,s} q_b t_{p,s} f_{w,s} \leq G \quad \forall \quad w \in W \tag{17}$$

$$\sum_{c=1}^{C} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} \sum_{w=1}^{W} x_{b,p} y_{p,s} e_{w,c} l_{b,c} a_{w,c} z_{w,b,s} q_b t_{p,s} f_{w,s} pot_s \zeta \leq E \tag{18}$$

$$\begin{gathered} l_{b,c}, a_{w,c}, z_{w,b,s} \in \{0,1\}, \\ q_b \in z^+ \end{gathered} \tag{19}$$

As mentioned before, from equations (1) and (2) the FO_1 is modeled as the sum of the variances of the production times of the serus and of the workers (3). It should be clarified that the model assumes that a product cannot be processed in the next workstation until it is completely processed in the immediately preceding workstation. With respect to the FO_2, the total energy consumption in production is obtained from the product between the total time required to perform a task and the power in kilowatts of the machine used to carry out that task (4). The result of this objective function is the energy consumption measured in $kilowatts * minute$.

The model restrictions are found in equations (5) - (19). The first restriction (5) ensures that each batch is assigned to a single seru. Similarly, constraint (6) ensures that each worker is assigned to only one seru. The third restriction guarantees that a task is performed only by workers that are trained to perform the task (7). Constraint (8) ensures that each task in each batch can only be performed by one worker, as long as the batch size is greater than zero. Restriction (9) limits the number of workers in each seru to N and restriction (10) limits the number of tasks assigned to a worker in a batch to M. Restriction (11) guarantees that for each task in a batch assigned to a seru there is at least one worker trained to carry out that task in the same seru. Restriction (12) prohibits a task from being performed by a worker that is not in the same seru as the batch that requires that task. Restrictions (11) and (12) prevent movement of batches and workers between serus. Restriction (13) ensures that all workers perform at least one task from each batch assigned to the same seru. Constraint (14) ensures that the demand for each product is satisfied. Constraints (15) and (16) model the relationship between the variables ex_b and q_b. The restriction (17) ensures that the total time used by a worker in production does not exceed its available time and the restriction (18) guarantees that the upper bound of grams of CO_2 generated in production is not exceeded.

The model presented is not linear given that there are multiplication of variables in the restrictions and in the objective functions. To obtain a linear model, the auxiliary variables $D_{c,b,w} = l_{b,c} \cdot a_{w,c}$, $H_{c,b,w,s} = D_{c,b,w} \cdot z_{w,b,s}$ and $R_{c,b,w,s} = H_{c,b,w} \cdot q_b$ are created. $D_{c,b,w}$ and $H_{c,b,w,s}$ are binary variables since they result from the multiplication of binary variables. The variable $R_{c,b,w,s}$ belongs to the set of positive integers including zero. To model these auxiliary variables the following restrictions are added to the model:

$D_{c,b,w}$ linearization:

$$D_{c,b,w} \leq l_{b,c} \forall c, b, w \tag{20}$$

$$D_{c,b,w} \leq a_{w,c} \forall c, b, w \tag{21}$$

$$D_{c,b,w} \geq l_{b,c} + a_{w,c} - 1 \forall c, b, w \tag{22}$$

$H_{c,b,w,s}$ linearization:

$$H_{c,b,w,s} \leq D_{c,b,w} \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{23}$$

$$H_{c,b,w,s} \leq z_{w,b,s} \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{24}$$

$$H_{c,b,w,s} \geq D_{c,b,w} + z_{w,b,s} - 1 \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{25}$$

$R_{c,b,w,s}$ linearization:

$$R_{c,b,w,s} \geq q_b - (1 - H_{c,b,w,s}) \sum_{p=1}^{P} d_p x_{b,p} \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{26}$$

$$R_{c,b,w,s} \leq q_b \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{27}$$

$$R_{c,b,w,s} \leq H_{c,b,w,s} \sum_{p=1}^{P} d_p x_{b,p} \quad \forall \quad c \in C, b \in B, w \in W, s \in S \tag{28}$$

The above restrictions are added to the model and the auxiliary variables are replaced in equations (12), (13), (17) and (18). To linearize the model, it must also be considered that FO_1 has quadratic terms. According to [6] the minimization of the sum of squares contained in the variance of production times between serus and between workers, can approximate the difference between the maximum and the minimum time of production of serus and workers, respectively. However, the maximum and minimum functions are not linear. To linearize them, four additional variables are created each with an associated restriction that forces them to take the maximum or minimum value of the inter-seru or intra-seru production time. In equations (29 - 32) the new variables of the model are defined. These constraints and auxiliary variables must also be added to the model. All these new auxiliar variables are continuous and non-negative.

$$I \geq \sum_{w=1}^{W} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} e_{w,c} R_{c,b,w,s} t_{p,s} f_{w,s} \quad \forall \quad c \in C \tag{29}$$

$$J \leq \sum_{w=1}^{W} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} e_{w,c} R_{c,b,w,s} t_{p,s} f_{w,s} \quad \forall \quad c \in C \tag{30}$$

$$K \geq \sum_{c=1}^{C} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} e_{w,c} R_{c,b,w,s} t_{p,s} f_{w,s} \quad \forall \quad w \in W \tag{31}$$

$$U \leq \sum_{c=1}^{C} \sum_{b=1}^{B} \sum_{p=1}^{P} \sum_{s=1}^{S} x_{b,p} y_{p,s} e_{w,c} R_{c,b,w,s} t_{p,s} f_{w,s} \quad \forall \quad w \in W \tag{32}$$

Replacing the new variables I, J, K and U in the equations WO_1 and WO_2 we get:

$$WO_1 = \frac{1}{C}(I - J) \qquad (33) \qquad\qquad WO_2 = \frac{1}{W}(K - U) \qquad (34)$$

4 NSGA-II based algorithm

The following is the NSGA-II based genetic algorithm developed to solve large instances of the production planning problem. To create the structure of the chromosomes, the encoding presented by [1] was taken from the layers whose alleles represent the decision variables $l_{b,c}$, $a_{w,c}$ and $z_{w,b,s}$, this means, the second and third layer.

4.1 Encoding

Each chromosome is made up of three layers. Said layers are made up of alleles that represent the values of the decision variables presented in the mathematical formulation of the problem. The alleles in the first layer represent the value of the decision variable q_b. Let n_C be the number of serus available in production, n_P the number of types of product demanded and n_B the number of batches available, the length of the first layer is $L_1 = n_C * n_P = n_B$. This structure allows each product to be distributed in as many batches as Serus are available. The parameter $x_{b,p}$ defined above, determines the type of product for each batch. In order to guarantee compliance with the demand for each type of product, the sum of the batch sizes of a type of product must be equal to the value of its demand. The batch size is allowed to be zero, therefore, the binary decision variable ex_b will also take this value.

The second layer of the chromosome determines the assignment of batches and workers to the serus. The alleles of this layer can take values that are within the set of serus ($C = 1, \ldots, n_C$). Consequently, alleles allow setting the values of the decision variables $l_{b,c}$ and $a_{w,c}$. This layer is made up of two lists. The length of the first list is n_B and the length of the second list is n_W, that is, the number of available workers. Thus, the second layer has a length $L_2 = n_B + n_W$. The positions of the genes in each list make it possible to identify which batch or worker is being referred to and the allele value of each gene determines the seru to which the corresponding batch or worker was assigned. In the case in which a batch is assigned a value of zero units in the first layer ($q_b = 0$), the position of that batch in the first list of the second layer will have an allele with the value 'None'. In order to generate better solutions, it is guaranteed that each seru has at least one worker and one assigned batch. This is achieved by assigning each allele with each Seru to a gene on the first and second lists of the second layer of the chromosome. Batches and workers that have not been assigned are randomly assigned to any Seru.

The last layer of the chromosome allows to determine the value of the decision variable $z_{w,b,s}$. This layer is made up of as many lists as batches. Each of the lists represent a batch ($B = 1, \ldots, n_B$). A list has as many genes as tasks required by the corresponding batch. Thus, with S_b being the number of tasks in a batch b,

the length of the third layer is $\sum_{b=1}^{B} S_b$. The position of each gene within a list represents a task from that batch. The allele of each gene determines the worker ($W = \{1, \ldots, n_W\}$) who will perform the task. In the case in which a batch is assigned a value of zero units in the first layer of the chromosome ($q_b = 0$), the list corresponding to that batch will be empty in the third layer. For the worker-task assignment, it must be ensured that if a worker is to perform the task of a batch, they must be trained to perform it. Additionally, it must be in the same seru of the batch with the task that was assigned to it.

4.2 Feasibility correction

Once the initial population is created, infeasible chromosomes may appear that violate some of the constraints of the linear model. One of the infeasibility may be due to some tasks not being assigned. This infeasibility refers to the alleles of the third layer that take values of 'None'. This happens when there is no competent worker to perform a specific task in a seru. To correct this infeasibility, two scenarios are considered. In the first scenario, the infeasible batch is the only one in the seru. In this case, workers from other serus skilled to perform the problematic task and if they are not the only workers from their Serus , should be selected. When one is randomly selected the second and third layer are modified. In the second case, the infeasible task does not belong to the only batch in the seru. In this scenario, the infeasibility is resolved by sending the problematic batch to another Seru where the assigned workers can execute the task.
Another infeasibility is that the maximum limit of workers per seru is exceeded. Again, two particular cases are conceived to correct this infeasibility. In the first case, the Seru that exceeds the maximum number of workers has a worker who is not assigned to any task in the seru. In this case, the serus that could receive an additional worker without becoming infeasible must be identified and the worker assigned to one of them randomly. The second case considers redundant workers that could be sent to another Seru without affecting the third layer. Redundant workers are those workers whose useful skills in the Seru are contained in the skills of the other workers of the same Seru. Once a redundant worker is sent to a Seru that can receive an additional worker, the second and third layers must be updated.
Additionally, it is not allowed for a worker to be assigned more than M tasks from the same batch. This infeasibility is prevented in the creation of the third layer of the chromosome when, when identifying the competent workers to perform a specific task, the number of times that the alleles of the batch have taken the value of that worker in the third layer is counted. If the worker is trained to do the task but has already been assigned M times to tasks of that batch, it is not taken into account to be assigned to more tasks of the same batch.
Finally, it may be occur that a worker assigned to a Seru is not assigned to any task from each batch of the Seru. To avoid this infeasibility, the creation of the third layer seeks to balance the load of workers so that if several workers are competent to carry out a task, the one who has assigned, so far, the least amount of tasks in the batch is selected. . Even with this balancing, it is possible to obtain

chromosomes that present this infeasibility. This is corrected by assigning the infeasible worker a task of another worker from the same Seru in which he is competent, provided that this is not the other worker's only task.

4.3 Fitness y penalty function

Fitness is calculated from the objective functions presented in the mathematical formulation and two penalty functions. The first step to obtain fitness is to determine the values of the decision variables according to the values that the alleles of the chromosome have taken in each layer. Subsequently, it is possible to obtain the value of the objective functions.

Now, there are still some infeasible chromosomes even after correcting the infeasibilities mentioned above. This is because the mathematical formulation contains two complex constraints that involve the relationship between all the decision variables. These correspond to the restriction that establishes the maximum working time per worker, and the restriction that limits the CO_2 emissions generated in production. Those chromosomes that violate any of these restrictions will be subjected to both penalty functions. This prevents the illegal chromosomes from being selected to pass to the next generation, therefore, it is also not possible that they have intercrossing for the generation of descendants. The penalty functions used for the fitness calculation are created from the penalty function proposed by [14]. and adapted by [1]. Given a chromosome i of the population P_t we have:

Δv_1(i) = constraint violation value (17) for chromosome i.
Δv_2(i) = constraint violation value (18) for chromosome i.
k = parameter that determines the severity of the penalty function.
G = maximum time available per worker.
ε = positive number tending to zero.
E = maximum CO_2 emissions allowed in total production.
Δv_1max = value of the maximum violation of constraint (17) in P_t.
Δv_2max = value of the maximum violation of the constraint (18) in P_t.

From the previous parameters it is possible to construct the penalty functions associated with the restriction (17) and (18) respectively:

$$penalFit1(i) = 1 + \left(\frac{\Delta v_1(i)}{\Delta v_1 max}\right)^k$$
$$\Delta v_1(i) = max\{0,\ g(i) - G\}$$
$$\Delta v_1 max = max\{\varepsilon,\ \Delta v_1(i) \mid i \in P_t\}$$

$$penalFit2(i) = 1 + \left(\frac{\Delta v_2(i)}{\Delta v_2 max}\right)^k$$
$$\Delta v_2(i) = max\{0,\ e(i) - E\}$$
$$\Delta v_2 max = max\{\varepsilon,\ \Delta v_2(i) \mid i \in P_t\}$$

The term $\Delta v_1(i)$ of the penalty function associated with restriction (17) must be calculated as $max\{0, g(i)-G\}$, where $g(i)$ is the total violation of chromosome

i, calculated as the sum of the chromosome workers violation times. Similarly, the term $e(i)$ of the penalty function associated with restriction (18) determines the CO_2 emissions of chromosome i in addition to those allowed (E).

Finally, we obtain the objective functions adjusted by the penalty functions. In order to prevent an illegal chromosome from being part of the pareto frontier, each objective function is multiplied by both penalty functions. Thus, if a chromosome violates the maximum time available per worker but does not exceed the maximum CO_2 emissions, both target functions will be penalized.

$$FO_1Pen(i) = FO_1 * penalFit1(i) * penalFit2(i)$$
$$FO_2Pen(i) = FO_2 * penalFit1(i) * penalFit2(i)$$

4.4 Crossover

To generate the crossover, only the first layer of the chromosome is considered. The above, taking into account that successive layers are built from this layer. For the interbreeding, the parents who have had a better performance in the selection tournament are selected. To generate the crossover, a random number must be selected among the types of product demanded ($P = 1, \ldots, n_P$). Subsequently, the batches of the randomly selected product must be exchanged between the parents. In this way, the distribution of the batches of the other products is maintained. Finally, the second and third layers of the descendants are generated from the result of the first layer.

4.5 Mutation

The mutation only applies to the first layer of the chromosome. A random number must be selected among the types of product demanded ($P = 1, \ldots, n_P$). Subsequently, the batch size of the selected product type must be recalculated. Once the mutation is made, the second and third layers are updated and the infeasibilities that occur in the chromosome are corrected. The mutation rate (p_m) must be very low in order to maintain elitism in the solutions.

4.6 Replacement

Once the genetic operators have been defined, the iterations of the metaheuristics begin. The first iteration differs from the following and must start with the random creation of a starting population $P(0)$ of desired size $nPob$. Population initiation is carried out as previously described. Then, the selection tournament is carried out among the individuals of the initial population, obtaining the non-dominance rank and the distance to the crowd of each chromosome. This allows you to sort individuals according to their fitness and the density of nearby solutions. In this first iteration, all the individuals of the initial population go to the next generation $P(t + 1)$. To double the size of the population, the chromosomes arranged according to the selection tournament are crossed, giving rise to two descendants, in this way a population of descendants of size $nPob$ called

$Q(t)$ is created. The individuals of this last set are subjected to mutation with a probability p_m. Finally, a population of size $2nPob$ is obtained by the union $P(t) + Q(t)$.

For the following iterations, the procedure shown in algorithm is followed. The population $R(t)$ of size $2nPob$ is submitted to the selection tournament, obtaining 1) the non-dominance ranges and 2) the distance from the crowd of each individual. The individuals are selected according to the selection tournament to pass to the next generation P(t+1) of size $nPob$. This is done by prioritizing chromosomes with a lower non-dominance rank. If when adding all the individuals of a particular front the size $nPob$ is exceeded, priority is given to the chromosomes of the front that have a greater distance from the crowd. This population $P(t + 1)$ is crossed to obtain the population $Q(t)$ of size $nPob$. The population $Q(t)$ is mutated to add variability. Finally, the population $R(t)$ of size $2nPob$ is obtained and it is iterated again until the maximum number of generations is reached.

5 Analysis of results

In order to calculate the efficiency of the proposed metaheuristic algorithm, a small instance is solved with the exact method and the NSGA-II, thus obtaining two comparable pareto frontiers. For the creation of the instance, the following specifications are taken into account:**1.** The number of serus and number of workers is 2. **2.** The number of batches is 4. **3.** The number of tasks / skills is 5. **4.** The demand for each of the products follows a distribution $U(10, 70)$. **5.** The processing time of the tasks follows a $U(10, 70)$ distribution. **6.** The proficiency obeys a distribution $U(0.90, 1.10)$ **7.** The maximum number of workers per seru and tasks per worker is 3. **8 .** The size of the skill set per worker is a random integer between [3,5].

Figure 1 shows the solutions found through the NSGA-II. Additionally, it is possible to determine each one of the fronts obtained in the final generation. The approximate pareto frontier is the one generated by the solutions of the first non-dominated front, that is, those solutions that have a non-dominance rank equal to zero. To run the NSGA-II, the following parameters were taken into account: **1.** Mutation rate $(p_m) = 0.025$ **2.** Population size $(nPob) = 60$ **3.** Maximum generation $(maxGen) = 90$ textbf 4. Penalty coefficient $(k) = 2$.

Through the ε - constraint method proposed by [9], the pareto frontier of the multi-objective linear optimization model is generated. Next is presented the optimal pareto frontier obtained through the multi-objective linear optimization model and the approximate pareto frontier obtained when selecting the solutions of the first non-dominated frontier of the maximum generation of the NSGA-II. Finally, to obtain a notion of the efficiency of the metaheuristic and the proposed encoding, the comparison of both borders is made by calculating the areas under the curve of each of the borders, setting the minimum and maximum value on the x axis (dotted lines). With the results of the areas, the proportion of the

area of each method is calculated by making 15 runs of the algorithm to obtain more reliable measurements. An average gap value of 2,773 % is determined.

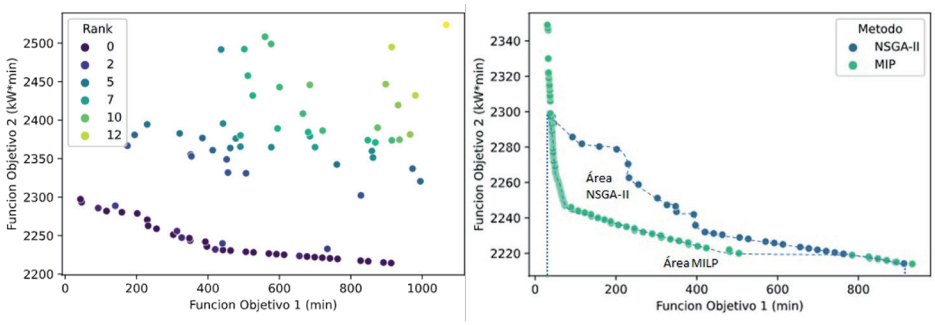

Fig. 1. Comparación frontera NSGA-II y MILP

6 Conclusions and future work

With the accelerated increase in CO_2 emissions into the atmosphere and global connectivity that boosts demand, the seru production system could be the answer to maintain competitiveness given its economic and environmental benefits and its flexibility in the face of unexpected changes in demand. The concept of heterogeneous workers makes it easy to reconfigure the system in the face of unexpected changes in the production environment.

It is evident that the variables q_b and ex_b of the exact model allow greater flexibility to carry out the assignment of batches, workers and tasks since it is possible to produce a fraction of the demand for a type of product in each of the available serus. The algorithm based on NSGA-II demonstrates a good solution regarding the optimal boundary generated with the MILP, allowing to find good solutions to the production planning problem in a reasonable computational time.

For future studies, it is proposed to identify in which other industries, apart from the tech inustry, the seru production system could be adapted and simulate it in a real case of the to quantify its benefits. Additionally, a more accurate study of the production time of a batch must be carried out, considering the WIP. On the other hand, given that the seru production system focuses on workforce, it is proposed to introduce qualitative measures such as the learning curve, teamwork and autonomy to determine how the performance of the system could be improved and what configurations of seru should be used in specific production environments.

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Proceso de toma de decisión multicriterio aplicado a máquinas de una línea de producción

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Abstract. En toda planta de producción, un aspecto clave que debe ser considerado es el análisis integral de las máquinas, ya que estas tienen un impacto en la producción. Además, es sabido que existe una demanda creciente de los productos y un constante avance tecnológico del sector industrial. En este contexto, se pretende contribuir con una metodología que facilite la planificación del mantenimiento de las máquinas, a fin de mejorar la producción. Así, el objetivo principal del trabajo es la priorización de máquinas que componen una línea de envasado de latas de cerveza, considerando sus atributos, un registro de fallas y el cálculo de producción que se ha perdido. Se ha realizado una recolección de datos basado en las fallas de las máquinas, para luego realizar una investigación descriptiva, de naturaleza empírica y documental, sustentada en fuentes primarias y secundarias donde se estudiaron casos de eventos de seguridad y calidad, que han ocurrido en plantas similares de la misma empresa. Los resultados obtenidos muestran que es posible definir un listado de priorización de máquinas en función a una evaluación en el que se ha utilizado múltiples criterios, mediante la herramienta de decisión denominada Proceso Analítico Jerárquico (AHP). Asimismo, se han realizado simulaciones de fallas no programadas de las máquinas y finalmente, un análisis de sensibilidad de las decisiones tomadas, de tal manera a observar la robustez de los mismos. Con esto, se buscar brindar una herramienta de decisión con el fin de mejorar la gestión de mantenimiento de la empresa.

Keywords: Máquinas, Línea de Producción, Proceso Analítico Jerárquico (AHP), Toma de decisión, Criterios de evaluación.

1 Introducción

En Paraguay, las quince actividades económicas principales del sector industrial absorben el 79,1% del total de ingresos y concentran el 22,5% del total de unidades económicas. La actividad económica con mayores ingresos por el suministro de bie-

nes y servicios, es la dedicada a la generación, transmisión y distribución de energía eléctrica con el 25,8% del total de ingresos de las unidades económicas del país, seguida del procesamiento y conservación de carne con el 15,3%, luego la elaboración de productos del tabaco con el 5,0%, posteriormente la elaboración de otros productos alimenticios con el 4,2%, y finalmente, en el ranking de las cinco primeras actividades económicas, se encuentra la elaboración de bebidas alcohólicas con el 3,2% [1].

En este contexto, en cuanto a la industria cervecera del país, la compañía Cervecería Paraguaya S.A. (CERVEPAR), es una de las más representativas, la misma sigue apostando al desarrollo de la industria local, a través de inversiones que tendrían un alto impacto en la economía local. Esto no sólo sería en beneficio de la cadena de valor de la industria, sino en la percepción de los demás actores económicos [2]. Cabe resaltar que, en los últimos 5 años, Cervepar realizó inversiones por más de USD 175 millones en el país. El aporte tributario de la compañía en los últimos 5 años alcanza la suma de USD 320 millones. La comercialización de los productos de la compañía genera un movimiento comercial de USD 591 millones, esto representa el 1,6% sobre el PIB, y el 5% del sector terciario [3].

Por lo tanto, mencionada la importancia de dicha compañía para el país, el presente trabajo se ha enfocado a la industria cervecera, donde se ha analizado el sector de envasado de cervezas de dicha compañía. Ésta investigación tiene como principal misión brindar una herramienta de toma de decisión a los ingenieros encargados de la planificación del mantenimiento de la línea de producción, buscando una mayor confiabilidad en los planes de mantenimiento de las distintas máquinas que componen una línea de envasado. Con esto, se pretende mejorar las funciones del personal de la línea, y tener un adecuado control de la producción, considerando la priorización de las máquinas y con esto, realizar intervenciones estratégicas.

Para llevar a cabo el trabajo, se han realizado simulaciones de paradas no programadas, éste utiliza un esquema automatizado de la línea de producción, de tal forma a extraer del mismo, informaciones de producción (tiempo de paradas, motivos y cálculo de producción perdida). Dichas informaciones fueron registradas en una bitácora de eventos, donde los datos y registros de producción fueron utilizados para el análisis de la priorización de las máquinas. Además, han sido analizados datos estadísticos relevantes de las máquinas como, por ejemplo: datos de eventos de seguridad y calidad ocurridos en plantas de producción similares, en los últimos dos años.

2 Proceso de toma de decisión

En el área de toma de decisiones, la toma de decisión multicriterio es tal vez, una de las técnicas más utilizadas, la misma se denomina *Analytic Hierarchy Process* (AHP). El Proceso Analítico Jerárquico fue desarrollado durante los años setenta, por el matemático Thomas Saaty, buscando el desarrollo de una herramienta sistemática para la determinación de un ranking de alternativas que tenga un fundamento matemático sólido y que sea simple en su aplicación [4]. Esta metodología es utilizada para resolver problemas complejos que utilizan múltiples criterios de evaluación, donde es necesario que quien analiza el problema otorgue un nivel de preferencia subjetiva res-

pecto a la importancia de cada criterio y que posteriormente especifique una preferencia de cada alternativa en función a cada criterio, utilizando una escala.

El AHP ayuda a determinar escalas relativas utilizando una ponderación de datos de una escala estandarizada, realizando una operación aritmética posterior en tales escalas. Por lo tanto, las ponderaciones se dan en forma de comparaciones por pares. Para ello, se asume de que existen varios criterios, cuyos pesos son respectivamente conocidos. En el proceso se determina una matriz de relación por pares, cuyas filas dan las relaciones de pesos de cada criterio con respecto a todos los demás.

Primeramente, es necesario conformar un árbol jerárquico de decisión, para ello es necesario conocer el objetivo del problema abordado, para luego establecer los criterios a ser evaluados y las alternativas a ser consideradas como comparables en el proceso de toma de decisión. La distribución de dicho árbol puede tener tantos niveles como sea necesario, en el nivel superior se encuentra el objetivo principal a lograr, en los niveles intermedios se encuentran los criterios de evaluación y en los niveles inferiores se localizan las alternativas a ser consideradas como comparables [5].

El segundo paso consiste en la ponderación obtenida de la comparación por pares. Los elementos del segundo nivel están dispuestos en una matriz y las ponderaciones de los criterios, son realizadas con relación al objetivo principal. Generalmente, la metodología utiliza una ponderación con valores de una escala, de 1 al 9, como se describe en [4]. Luego de conformar la matriz de comparaciones pareadas de los criterios, se puede obtener el vector resultante de dichas ponderaciones. Este vector se estima a través del autovector de la matriz.

El tercer paso consiste en la comparación por pares de los elementos en el nivel más bajo, es decir, las alternativas son comparadas con respecto a cada criterio de evaluación. En esta parte se evalúan las ponderaciones de cada alternativa con respecto a cada criterio, según [6]. Finalmente, se multiplica la matriz resultante de la ponderación de cada criterio por el vector resultante de la ponderación de cada alternativa en función de cada criterio, y este producto da como resultado un vector columna que representa la ponderación global de las distintas alternativas, en función de todos los criterios analizados.

La herramienta de decisión AHP ha sido utilizada en diferentes casos de estudio, con el objetivo de resolver diversos tipos de problemas, algunos de ellos son: [7] – [16]. Por lo tanto, el AHP es una metodología que permite evaluar las alternativas que se plantean a la hora de tomar una decisión.

3 Metodología propuesta

3.1 Contexto actual de Cervepar

Actualmente, la compañía CERVEPAR, fundada en el año 1910, se ha convertido en la mayor planta industrial de bebidas del Paraguay. La misma cuenta con seis líneas de producción en el sector de envasado, dotando a la planta de una capacidad de envasado de 1.000.000 de litros de cerveza por día. Sin embargo, con el paso del tiempo y el avance tecnológico, es de esperarse que surjan nuevos problemas que deben ser solucionados. Se ha evidenciado la necesidad de automatizar procesos en el área de

envasado, para de esta manera mejorar el nivel de productividad de las líneas. Considerando esta situación, en una de las líneas de producción dedicada al envasado de latas, se ha comprobado que, al momento de producirse una parada no programada, la recolección de datos del evento ocurrido representa un problema importante, ya que, al producirse la parada, un operador necesariamente debe recorrer toda la línea para identificar el problema, y en base a observaciones directas, determinar el motivo de la parada y el tiempo de duración. Este procedimiento posibilita la existencia de errores humanos, lo que genera inconvenientes a la hora de realizar un análisis post-falla, aumentando la dificultad de tener una visibilidad clara acerca de la eficiencia productiva de cada máquina.

En ese sentido, el presente trabajo tiene por objeto proponer una metodología de decisión, el cual implica un esquema de automatización y simulación para el proceso de recolección de datos de paradas no programadas. Con esto, sería posible tener una mayor confiabilidad en el cálculo de la eficiencia de producción, sin intervención manual en el registro. La aplicación de conocimientos de automatización de procesos ayudaría a ahorrar tiempo en el momento de categorizar las distintas máquinas y a evidenciar los problemas que puedan surgir, al ocurrir cualquier tipo de evento. Asimismo, la aplicación de este esquema permitiría cuantificar el volumen de producción que se ha perdido al ocurrir una falla, teniendo en cuenta el tiempo de parada de la máquina y finalmente, traducir esos datos en términos de costos. Con esto, se pretende dar una visibilidad diferente a los problemas analizados y permitir al equipo de trabajo enfocarse en los puntos críticos, buscando mejorar el uso de recursos necesarios para el mantenimiento de la línea.

3.2 Criterios de evaluación

El AHP es una metodología utilizada para resolver problemas de decisión, en el que se consideran indicadores cuantitativos y cualitativos. Para dicha resolución se utilizan múltiples criterios de evaluación, donde es necesario que el tomador de decisiones otorgue un peso o preferencia al momento de realizar las comparaciones pareadas. Esta decisión debe ser subjetiva y se basa en una escala de preferencias, esta escala se denomina escala de Saaty [4]. El proceso de decisión se ha realizado dándole un peso a cada alternativa (máquina), en función a tres criterios de evaluación definidos, estos se han determinado de acuerdo a la experiencia de los decisores, para finalmente conformar una matriz de priorización de máquinas. En la Fig. 1, se puede ver el árbol jerárquico de decisión utilizado en el proceso de toma de decisión. Posteriormente, se describen los criterios de evaluación utilizados en el análisis.

Impacto Económico: para este criterio se evalúa el impacto de una parada de máquina, para ello se realizaron simulaciones de paradas habituales en cada una de las máquinas que componen la línea de envasado, con el fin de cuantificar el volumen perdido de producción en cada parada. Una vez cuantificado y obtenido los datos del volumen perdido, el mismo es valorizado según históricos de costos de producción [15], para luego utilizarlo como dato de entrada al modelo de toma de decisión, y así obtener el vector propio de este criterio.

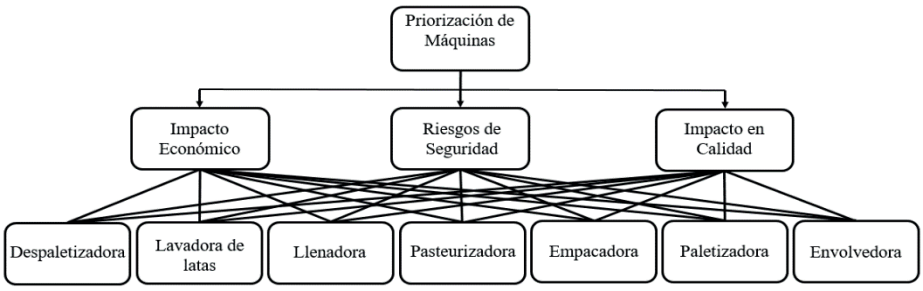

Fig. 1. Árbol jerárquico de decisión (Fuente: Elaboración propia)

Riesgos de Seguridad: para este criterio se tuvo en cuenta la seguridad, considerando qué tan crítica es una intervención de mantenimiento en cada una de las máquinas de la línea. Para ello, se han utilizado como datos de entrada al modelo de decisión, la base de datos de antecedentes históricos de eventos ocurridos en plantas similares; dichos eventos ocurrieron en el periodo 2016 - 2018 [17], [18]. Finalmente, con esto se pudo calcular el vector propio de este criterio.

Impacto en Calidad: para este criterio se consideró el impacto de la calidad del producto terminado, considerando la falla que se tuvo en el proceso de los productos. Para esto, se ha considerado como datos para el modelo de decisión, la cantidad de incidentes de calidad relacionados a las fallas de cada una de las máquinas durante el periodo 2016 - 2018 [17], [18]. Así, con esto se pudo hallar el vector propio de este criterio.

3.3 Alternativas

Las alternativas consideradas comparables para el análisis de este trabajo se pueden observar en el último nivel de la Fig. 1, dichas alternativas son máquinas que se encuentran en operación en una línea de envasado de latas de la compañía Cervepar. Las alternativas analizadas son las siguientes máquinas: Despaletizadora, Lavadora de latas, Llenadora, Pasteurizadora, Empacadora, Paletizadora y Envolvedora.

4 Caso de estudio

4.1 Simulaciones

Para llevar a cabo las simulaciones de la línea de envasado, se ha recurrido al lenguaje de programación © Python, además, como software de simulación se ha utilizado VirtualBox de © 2020 Oracle, ambos programas en sus versiones gratuitas.

La línea de envasado de latas utilizada como caso de estudio pertenece a una línea de producción de la empresa Cervepar, ésta consta básicamente de siete partes llamadas islas automáticas, unidas entre sí por medio de cintas transportadoras. Cada isla es controlada por un PLC, el cual mediante una programación almacenada dentro del mismo realiza procesos de maniobra, control, señalización, temporización, etc.

La función de conteo es realizada a través de sensores de cada máquina, donde se van adquiriendo datos de los conteos de producción y el estado propio de la máquina. Los datos de los sensores se parametrizan como entradas digitales dentro del PLC de las máquinas. Las siete islas automáticas ya fueron mencionadas, ellas son: Despaletizadora, Lavadora de latas, Llenadora, Pasteurizadora, Empacadora, Paletizadora y Envolvedora.

El simulador es una herramienta de gestión que facilita al operador la interpretación de los datos referente a la producción obtenida en un periodo de 24 horas. Facilita la observación de los eventos que pudieran darse relacionados a la eficiencia de la máquina, con el fin de generar soluciones en tiempo real, adecuadas a situaciones específicas en el caso de fallas, lo cual posibilita mejorar la producción y el trabajo del personal. En la Fig. 2 se puede observar una visualización general del simulador de línea.

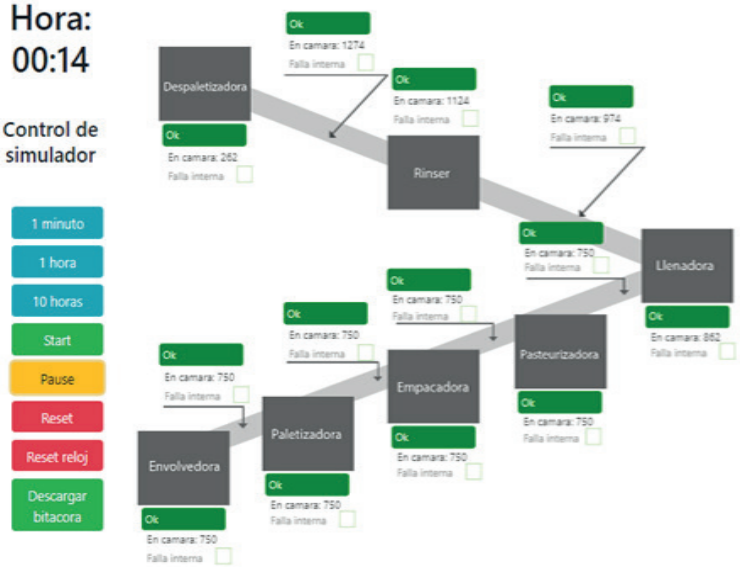

Fig. 2. Simulador de línea de envasado (Fuente: Elaboración propia)

Cada máquina tiene programada una cantidad de modos de falla. Cabe resaltar que existe un modo de falla común, tanto para las cintas transportadores como para las máquinas, llamada falta de alimentación. Esta falla se da cuando se tiene faltante de producto o acumulación del mismo. Cada máquina posee una interfaz del simulador, que contempla un botón llamado falla interna. Dicha opción ofrece la posibilidad de acceder al informe de las fallas, la cual es visualizada a través de una bitácora de eventos, y ésta contempla la cantidad de latas no producidas durante la parada.

4.2 Descripción de las funciones del simulador

El simulador desarrollado cuenta con las siguientes funcionalidades:
- Permite tener un control del tiempo de simulación de la producción en un periodo de 24 horas, de modo a tener un registro de los eventos ocurridos.

- Cuenta con un panel de botones de comando, donde el operador puede iniciar la simulación, pausarla, resetearla o adelantarla.
- Cuenta con una representación en forma de bloques de la línea de producción, donde se detalla el estado de cada máquina y transportes que componen la misma, pudiéndose ver el status de cada máquina.
- Despliega una lista de fallas típicas de cada máquina.
- Dispone de una bitácora de eventos donde se registran las paradas.

4.3 Concepto de ¨V¨ de línea

Se ha considerado este concepto para la realización de las simulaciones, el mismo se basa en el balance de línea. Dicho balance se considera al funcionamiento adecuado de cada una de las máquinas que conforman la línea, vinculada directamente a la configuración de las velocidades y ubicación de cada una de ellas. El balance es indispensable para asegurar el funcionamiento ideal de la línea de producción, lo cual asegura la producción adecuada de la misma, teniendo en cuenta la configuración previamente establecida. En el caso de la línea de latas, la misma está compuesta por siete máquinas que poseen ciertos parámetros de velocidad (dichos parámetros son configurados en consenso con el encargado del diseño del proyecto y el proveedor de la línea).

Este concepto, básicamente expresa que el balance de línea debe darse con distintas velocidades, dependiendo de la ubicación y función que tenga la máquina en la línea de producción. Sin este concepto, el diseño de una línea de producción no puede llevarse a cabo. En este caso, las máquinas presentan las siguientes velocidades:

- Despaletizadora: 135% de la velocidad nominal
- Lavadora de latas: 125% de la velocidad nominal
- Llenadora: 100% de la velocidad nominal
- Pasteurizadora: 115% de la velocidad nominal
- Empacadora: 120% de la velocidad nominal
- Paletizadora: 125% de la velocidad nominal
- Envolvedora: 135% de la velocidad nominal

Por concepto, la máquina que define la velocidad nominal de una línea, es la Llenadora, ya que es la encargada de llenar con cerveza el recipiente y es directamente cuantificable como producto terminado cuando pasa por la misma. Es así, como cada máquina debe ser ajustada para que el balance de línea ocurra. Como se ha dicho, las máquinas que anteceden y suceden a la Llenadora son más veloces, debido a que, por la separación de las cintas transportadoras, ellas deben de compensar esa separación con velocidad superior, de modo a no tener paradas por alimentación o acumulación del producto. Por último, el espacio entre máquinas representa a las cintas transportadoras en una línea de producción. Si bien no tienen una velocidad propia, son dependientes de las velocidades y rendimientos en régimen normal de las máquinas que le suceden o anteceden. Las mismas actúan de “pulmones”, debido a que pueden contener una cierta cantidad de producto y en el caso de que alguna máquina sufra una falla o parada menor, la eficiencia y rendimiento de la línea de producción no se ve afectada, siendo el ejemplo ideal de la aplicación del concepto de “V” de línea.

4.4 Aplicación de la técnica del AHP

Esta investigación analiza un caso de estudio que supone las alternativas anteriormente mencionadas, bajo los criterios de evaluación citados, estructurados de forma fundamental en el árbol jerárquico. El objetivo principal del trabajo es el de determinar la priorización de las máquinas que componen una línea de envasado. Para ello, es utilizado la metodología Proceso Analítico Jerárquico (AHP).

4.5 Resultados de los Criterios de evaluación vs Alternativas

Impacto Económico: con el fin de cuantificar este criterio, se han realizado simulaciones de parada de máquinas, de manera a responder a la pregunta: ¿Cuál es el valor de la producción que se ha perdido en una parada de una hora de duración? Una vez conocidos los valores de producción perdido, a cada máquina se le asigna un peso según la escala de Saaty. En este trabajo se han considerado paradas de una hora para todas las máquinas, obteniéndose los siguientes resultados de la Tabla 1.

Tabla 1. Latas no llenadas por máquina.

Alternativas	Latas no llenadas	Precio unitario	Total Gs.
Despaletizadora	43500	1240	53.929.444
Lavadora de latas	42250	1240	54.859.262
Llenadora	45000	1240	55.789.080
Pasteurizadora	39000	1240	48.350.536
Empacadora	18750	1240	23.245.450
Paletizadora	12750	1240	15.806.906
Envolvedora	12000	1240	14.877.088

Teniendo en cuenta datos históricos, el costo de producción promedio de una lata se puede valorar en Gs. 1.240 (Guaraní: Gs., moneda de curso legal del Paraguay). Con esta información es posible calcular el valor del producto no llenado, multiplicando el precio unitario por la cantidad de latas no llenadas, obteniendo así los resultados de la Tabla 1.

Para comparar todas las alternativas con respecto a cada uno de los criterios de evaluación, es necesario ponderar cada alternativa con un peso según la escala de Saaty. Para esta parte del proceso de decisión, se estableció un rango de pérdidas al que se le asignó una valoración de 1 al 5. Dichos rangos fueron calculados dividiendo en cinco partes iguales, el rango de montos definidos por el valor máximo y el valor mínimo obtenidos en las simulaciones, según se puede observar en la Tabla 2.

Tabla 2. Escala de ponderación de valores.

Valor mínimo	Valor máximo	Pesos para el AHP
14.877.088	23.059.486	1
23.059.486	31.241.885	2

31.241.885	39.424.283	3
39.424.283	47.606.682	4
47.606.682	55.789.080	5

Considerando dichos rangos de valores, a cada máquina se le asigna un puntaje en función a la producción que se ha perdido, esta valoración se puede ver en la Tabla 3.

Tabla 3. Valorización de la producción no llenada.

Alternativas	Latas no llenadas	Precio unitario	Total Gs.	Pesos para el AHP
Despaletizadora	43500	1240	53.929.444	5
Lavadora de latas	42250	1240	54.859.262	5
Llenadora	45000	1240	55.789.080	5
Pasteurizadora	39000	1240	48.350.536	5
Empacadora	18750	1240	23.245.450	2
Paletizadora	12750	1240	15.806.906	1
Envolvedora	12000	1240	14.877.088	1

Con estos resultados, se puede observar que se tienen cuatro máquinas con paradas extremadamente críticas desde el punto de vista económico. Dichas máquinas son las siguientes: i) Despaletizadora, ii) Lavadora de latas, iii) Llenadora y, iv) Pasteurizadora. Para este análisis, la Llenadora resulta ser la más crítica, esto resulta lógico ya que una parada en la misma representa automáticamente un producto no llenado.

Riesgos de Seguridad: para cuantificar este criterio, se han considerado los datos históricos de eventos de seguridad ocurridos en líneas de producción de envasado de latas en plantas similares a Cervepar, considerando eventos de seguridad durante el periodo 2016 - 2018. Por lo tanto, considerando dicho periodo y la cantidad de eventos relacionados a la seguridad, se pudo elaborar la siguiente Tabla 4. Asimismo, para poder comparar el impacto económico con el impacto de seguridad, es necesario llevar ambos datos a una misma unidad de medida, considerando la escala de Saaty definida anteriormente. Estos rangos de valores fueron calculados dividiendo en cinco partes iguales, el rango formado por el valor máximo y el valor mínimo de la cantidad de eventos de seguridad ocurridos. Considerando dichos eventos, cada máquina tiene un puntaje según se puede observar en la Tabla 4.

Tabla 4. Eventos de seguridad ocurridos.

Alternativas	Total de eventos	Pesos para el AHP
Despaletizadora	22	2
Lavadora de latas	5	1
Llenadora	79	5

Pasteurizadora	38	3
Empacadora	10	1
Paletizadora	44	3
Envolvedora	22	2

Con este resultado parcial, se puede notar que, desde el punto de vista de seguridad, se puede identificar una máquina como extremadamente crítica y dos máquinas como medianamente críticas, como sigue: i) Llenadora, ii) Pasteurizadora y, iii) Paletizadora.

Impacto en Calidad: para el análisis y cuantificación de este criterio, se ha considerado la cantidad de incidentes de calidad relacionados a las fallas de cada una de las máquinas, durante el periodo 2016 - 2018. Es importante tener en cuenta que, se define como incidente de calidad a todo evento de producción que genera un producto no conforme con su calidad y debe ser retenido para su posterior inspección. El resultado de esta inspección puede derivar en la liberación del producto o derrame del mismo, en caso de que no cumpla con los parámetros de calidad establecidos. Por lo tanto, para dicho periodo, los incidentes de calidad relacionados a las fallas en las máquinas son los que se observan en la Tabla 5.

Tabla 5. Número de incidentes de calidad.

Alternativas	Incidentes	Pesos para el AHP
Despaletizadora	10	1
Lavadora de latas	50	4
Llenadora	66	5
Pasteurizadora	28	5
Empacadora	28	2
Paletizadora	25	2
Envolvedora	10	1

De manera análoga, considerando la cantidad de eventos de calidad registrados y unificando las unidades de medida con relación a los otros dos criterios de evaluación, se tienen los puntajes para cada máquina, ver Tabla 5. De igual manera al criterio anterior, fueron calculados rangos de valores, dividiéndolos en cinco partes iguales, conformando así el valor máximo y el valor mínimo de la cantidad de incidentes de calidad. Luego, se puede observar que, desde el punto de vista de la calidad, se identificaron una máquina extremadamente crítica y otra crítica, ellas son: i) Llenadora y, ii) Pasteurizadora. Para este análisis, la Llenadora resulta ser la más crítica, ya que una falla en la misma compromete directamente la calidad del líquido envasado.

4.6 Resultados de los Criterios vs Criterios

Antes de poder definir cuál de las máquinas es la más crítica, en función a todos los criterios de evaluación, es necesario hacerse la pregunta: ¿son todos los criterios igualmente importantes? Para este trabajo se ha decidido dar un peso relativo a cada

criterio, partiendo de la base que siempre la seguridad del personal y la calidad del producto terminado deben ser más importantes (mayor preferencia del decisor), que una posible pérdida económica. Por lo tanto, se ha asignado un peso a cada criterio, donde los mismos fueron evaluados de par en par, siendo el resultado el de la Tabla 6.

Tabla 6. Comparación pareada de criterios.

	Económico	Seguridad	Calidad	Vector propio
Económico	1	1/5	1/2	0,13
Seguridad	5	1	2	0,59
Calidad	2	1/2	1	0,28
Total	8	1,7	3,5	1

Como se puede apreciar, cada criterio comparado contra otro tiene un peso diferente, por ejemplo, el criterio de seguridad es extremadamente preferente con relación al criterio económico, ya que la seguridad del personal debe prevalecer siempre, por lo que, en la casilla correspondiente, se pondera con 5. Dicha ponderación, directamente en su forma recíproca, da una valoración de 1/5, cuando se compara el criterio económico con el de seguridad.

Posteriormente, para poder definir cuál de los tres criterios es más importante es necesario normalizar la matriz y hallar el promedio ponderado. Para realizar la normalización de la matriz primeramente debemos obtener la suma de cada columna para así conocer el puntaje acumulado de cada criterio. Además, se ha calculado el promedio ponderado de cada fila, el resultado de esta operación indica el nivel de preferencia de cada criterio. Como se puede ver en la Tabla 6, el criterio con mayor preferencia es el de Seguridad, seguido de la Calidad y, por último, el criterio Económico.

5 RESULTADOS

Finalmente, los resultados de los pesos previos obtenidos son agrupados para conformar la matriz de ponderaciones de alternativas respecto a cada uno de los criterios de evaluación; esta matriz es multiplicada por la matriz de ponderaciones de los criterios en función al objetivo principal. El producto de ambas matrices nos da como resultado la matriz de ponderación global de todas las máquinas en función de todos los criterios y las alternativas analizadas. El resultado de dicha multiplicación matricial puede observarse en la Fig. 3.

$$\begin{bmatrix} 5 & 2 & 1 \\ 5 & 1 & 4 \\ 5 & 5 & 5 \\ 5 & 3 & 5 \\ 2 & 1 & 2 \\ 1 & 3 & 2 \\ 1 & 2 & 1 \end{bmatrix} \times \begin{bmatrix} 0{,}13 \\ 0{,}59 \\ 0{,}28 \end{bmatrix} = \begin{bmatrix} 2{,}11 \\ 2{,}34 \\ 5{,}00 \\ 3{,}81 \\ 1{,}41 \\ 2{,}47 \\ 1{,}59 \end{bmatrix}$$

Fig. 3. Ponderación global de las máquinas (Fuente: Elaboración propia)

Para este caso de estudio, según la figura anterior, las máquinas más críticas son como sigue: i) Llenadora, ii) Pasteurizadora, iii) Paletizadora y, por último, iv) Empaquetadora, con el menor nivel crítico. Por su parte, con relación a los criterios de evaluación, el más importante es el criterio vinculado a la seguridad de los empleados, ya que estos intervienen en las paradas de mantenimiento de las máquinas. En segundo lugar, se encuentra el criterio relacionado a la calidad del producto terminado. Finalmente, en último lugar se encuentra el criterio vinculado a las pérdidas económicas.

5.1 Análisis de sensibilidad

Este análisis se lleva a cabo con el fin de examinar el grado de sensibilidad de los resultados obtenidos al variar el peso de los criterios de evaluación. El objetivo de este análisis es el de confirmar que los resultados obtenidos son robustos y no son frutos del azar. Este proceso consiste en variar el peso de un solo criterio de evaluación con respecto a los otros. Además, se varía el peso de dos criterios de evaluación con respecto a los otros. Para realizar el análisis de sensibilidad se ha dado ponderaciones diferentes a los criterios con respecto a su estado inicial, de esta manera se busca responder a la pregunta de, ¿qué pasa sí? por ejemplo, para el caso del criterio Impacto Económico se le asigna un mayor peso con relación a los demás criterios.

Primeramente, para este análisis en particular, se ha asignado el mismo peso a todos los criterios de evaluación. Los resultados de priorización de las máquinas se pueden ver en la siguiente Tabla 7.

Tabla 7. Priorización de máquinas con pesos iguales de todos los criterios.

Alternativas	Priorización (%)
Despaletizadora	12,53
Lavadora de latas	15,57
Llenadora	25,08
Pasteurizadora	21,16
Empacadora	8,07
Paletizadora	10,60
Envolvedora	6,98
Total	100

En la tabla anterior se puede observar que la alternativa con mayor peso corresponde a la Llenadora. Luego, se realiza la variación de peso del criterio Impacto Económico (con asignación de peso con valor 3), con relación a los otros dos criterios. Los resultados de priorización se pueden observar en la siguiente Tabla 8.

Tabla 8. Priorización de máquinas con mayor peso del criterio Impacto Económico.

Alternativas	Priorización (%)
Despaletizadora	15,85

Lavadora de latas	17,68
Llenadora	23,38
Pasteurizadora	21,03
Empacadora	8,18
Paletizadora	8,03
Envolvedora	5,85
Total	100

En la tabla anterior se puede observar que la alternativa con mayor peso también corresponde a la Llenadora. Posteriormente, se realiza la variación del peso del criterio Riesgos de Seguridad (con asignación de peso con valor 3), dejando fijo los otros dos criterios. Los resultados de priorización se pueden ver en la siguiente Tabla 9.

Tabla 9. Priorización de máquinas con mayor peso del criterio Riesgos de Seguridad.

Alternativas	Priorización (%)
Despaletizadora	12,23
Lavadora de latas	11,70
Llenadora	26,81
Pasteurizadora	19,75
Empacadora	7,20
Paletizadora	13,42
Envolvedora	8,89
Total	100

En la tabla anterior se puede observar que la alternativa con mayor peso sigue siendo la Llenadora. Por último, para esta parte del análisis, se realiza la variación del peso del criterio Impacto en Calidad (con asignación de peso 3), con respecto a los otros dos criterios. Los resultados de priorización de máquinas, para esta variación, se pueden ver en la siguiente Tabla 10.

Tabla 10. Priorización de máquinas con mayor peso del criterio Impacto en Calidad.

Alternativas	Priorización (%)
Despaletizadora	9,52
Lavadora de latas	17,34
Llenadora	25,05
Pasteurizadora	22,70
Empacadora	8,84
Paletizadora	10,36
Envolvedora	6,19

Total	100

De igual manera que las dos variaciones anteriores, en la tabla anterior se puede notar que la alternativa que presenta mayor peso es el de la Llenadora.

Finalmente, se puede decir que los resultados obtenidos de este análisis de sensibilidad dan como alternativa prioritaria a la Llenadora, lo cual demuestra que no varía con respecto al análisis inicial de la metodología propuesta. Se puede dar una mejor apreciación a lo dicho anteriormente, en la Fig. 4, donde la Llenadora, en color verde, permanece con el mayor peso, seguido de la Pasteurizadora y la Paletizadora.

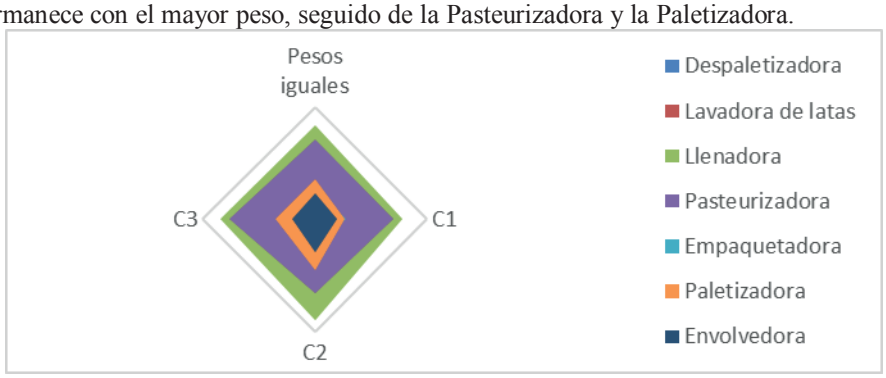

Fig. 4. Análisis de sensibilidad con variación de un criterio (Fuente: Elaboración propia)

Por último, cabe destacar que, realizando el mismo procedimiento en el marco del análisis de sensibilidad, pero con la variación de dos criterios de evaluación, se obtiene el siguiente comportamiento, demostrado por la Fig. 5, donde, de igual manera, el ranking de máquinas finalmente queda establecido por la Llenadora, Pasteurizadora y Paletizadora.



Fig. 5. Análisis de sensibilidad con variación de dos criterios (Fuente: Elaboración propia)

5.2 Conclusiones

La propuesta metodológica brinda una herramienta que primeramente obtiene información instantánea e histórica de producción de la línea, además identifica en cada etapa del proceso la velocidad de producción, la eficiencia y las fallas que ocasionan las paradas de máquinas indicando la causa.

El sistema detalla la estructura del sector de envasado de bebidas y permite conocer la ubicación y la descripción de las fallas en cada una de las islas, mediante los cuales, la solución y el seguimiento de los mismos se hacen más simples, para prevenir detenciones y mejorar el proceso de producción.

Al automatizarse la recolección de los datos de producción de la línea, se define un esquema de funcionamiento de controladores lógicos programables que permiten a los operadores evitar realizar los registros manualmente, pudiendo ellos dedicarse a otras tareas inherentes a la industria como la calibración, mantenimiento preventivo, entre otros.

La herramienta de simulación planteada es útil para categorizar a las máquinas en función a múltiples criterios, de manera a tener un mejor análisis y que sirva de información para el mantenimiento de las máquinas, la seguridad de los colaboradores y la calidad del producto terminado, creando una planificación estratégica para las inversiones e intervenciones futuras. Finalmente, se recomienda la adaptación de la presente propuesta metodológica a otras líneas de envasado.

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Estrategias de flexibilización de los sistemas de producción en la industria 4.0: un marco para su caracterización

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Abstract. This article presents a proposal for the characterization of strategies that have the purpose of increasing the flexibility of production systems (and therefore their adaptability), this in the context of industry 4.0. For this, a bibliometric analysis was carried out (specifically a study of co-occurrences), from which the categories included in the proposal are defined, this seeks to provide a framework for the evaluation and analysis of flexibility strategies of productive systems within in industry 4.0. After executing the bibliometric analysis, the proposed categories are: flexibility objective, level in the process engineering, level in the manufacturing process, required technologies and links in the supply chain involved. Associated with these categories, also as a product of the bibliographic analysis, possible levels are proposed for the categories.

Keywords: Industry 4.0, flexibility, adaptability, strategies categorization, production systems

Resumen. Este artículo presenta una propuesta para la caracterización de estrategias que tienen el propósito de incrementar la flexibilidad de los sistemas productivos (y por ende su capacidad de adaptación), esto en el contexto de la industria 4.0. Para ello, se realizó un análisis bibliométrico (concretamente un estudio de coocurrencias), a partir del cual se definen las categorías que se incluyen en la propuesta la cual busca proporcionar un marco para la evaluación y análisis de estrategias de flexibilidad de los sistemas productivos dentro en la industria 4.0. Tras ejecutar el análisis bibliométrico, las categorías propuestas fueron: objetivo de flexibilidad, nivel en la ingeniería de procesos, nivel en el proceso de fabricación, tecnologías requeridas y eslabones de la cadena de suministro involucrados. Asociados a estas categorías, y también como producto del análisis bibliográfico, se plantean posibles niveles para las categorías.

Palabras clave: Industria 4.0, flexibilidad, adaptabilidad, estrategia de categorización, sistemas de producción.

1 Introducción

Las operaciones globales de fabricación actuales exigen requisitos cada vez más estrictos, tales como plazos más precisos, niveles de inventarios competitivos, gestión de demanda incierta, estandarización de procesos y diversidad de productos [1]. Esto redunda en constantes y nuevos desafíos para los sistemas de manufactura, pues se les imponen el mantenerse a la vanguardia en estrategias de gestión que articulen eficientemente en su quehacer los recientes desarrollos tecnológicos.

La Industria 4.0, en adelante I4.0, representa un cambio hacia procesos de fabricación interconectados donde las entidades individuales dentro de la cadena de suministro se comunican entre sí con el fin de lograr tanto, una mayor adaptabilidad y capacidad de respuesta en la fabricación, como una fabricación más eficiente en términos de reducción en el costo de producción [1].

Es relevante contar con referentes, que en el marco de la Industria 4.0, contribuyan a las organizaciones en la evaluación y selección de estrategias para mejorar la capacidad su adaptación; un insumo fundamental para los procesos de evaluación y selección es la caracterización. Este artículo busca, a partir de una revisión de la bibliografía, proponer un referente de caracterización de estrategias propuestas para incrementar la flexibilidad de los sistemas productivos en la I4.0

Para ello, iniciamos con el planteamiento de los referentes que dan soporte a la acción de caracterizar, posteriormente se describe y desarrolla la propuesta metodológica, se presentan los resultados (la propuesta de caracterización), y se da cierre con las conclusiones derivadas del proceso llevado a cabo.

2 Referentes

El objetivo de esta sección es brindar un marco para la caracterización de estrategias a partir de criterios (categorías), de clasificación; se define la teoría de la clasificación como los principios que rigen la organización de objetos en grupos según sus similitudes y diferencias o su relación con un conjunto de criterios [2]. En el transcurso de este apartado se presentan las bases que soportaron la elección de los criterios usados para caracterizar las estrategias que en el entorno de la I4.0 se plantean para favorecer la capacidad de respuesta de los sistemas de producción. En términos generales, los referentes considerados abarcan aspectos relacionados con los componentes de la I4.0, sus principios de diseño, las estrategias para incrementar la capacidad de respuesta de los sistemas de producción en la I4.0, y las relaciones entre la I4.0 con los sistemas de apoyo a lo toma de decisiones.

2.1 Componentes y principios de diseño de la Industria 4.0

En los últimos años se ha presentado un auge en el estudio de las posibilidades que ofrece para el sector de la manufactura la cuarta revolución industrial. Existen estudios del estado del arte [3–7], propuestas de modelos de gestión [8–13], así como estudios en los que se analiza la flexibilización de la manufactura a través de elementos de la industria 4.0 [3, 14–16]. Han surgido múltiples estrategias para llevar a la manufactura a un nivel superior en términos de su adaptabilidad y productividad; se menciona también la necesidad de la selección de las estrategias apropiadas para la transición a la industria 4.0 desde una perspectiva multidisciplinaria [17]. Este interés sostenido e incremental por este campo se ha venido consolidando desde principios de esta década, cuando en la feria de Hannover (Alemania) (salón de la tecnología), fue incursionado el término, tomando mayor relevancia desde 2013 cuando se presentó un informe oficial y detallado del concepto y sus perspectivas (para la industria alemana) [18], también en la feria de Hannover.

La principal diferencia de la industria 4.0, respecto a sus predecesoras es la interacción de agentes autónomos en estructuras descentralizadas que se conectan entre sí con centros de decisión [19]. Dentro de las tecnologías provistas por la I4.0 más relevantes a los procesos de toma de decisiones están: la computación en la nube (*Cloud Computing*); el internet de las cosas, IoT por sus siglas en inglés (*Internet of Things*); *Big Data* y conexiones RFID (*Radio-frequency identification*) [19–21]

Los Sistemas Ciber-Físicos (CPS, *Cyber-Physical Systems*) [1], entendidos como sistemas de entidades computacionales colaboradoras que están en conexión intensiva con el entorno físico circundante y sus procesos en curso [22], y que cuentan con capacidad autónoma de intercambiar información, desencadenar acciones y controlarse entre sí de forma independiente [18], han allanado el camino a la transición del control centralizado a las arquitecturas de control descentralizado en la fabricación [23].

Los Sistemas de Producción Ciber-Físicos (CPPS, *Cyber-Physical Production Systems*) hacen parte de los sistemas sobre los que se plantea el aprovechamiento de la industria 4.0 en el ámbito de los procesos de fabricación. Monostori [24] define los CPPS como un conjunto autónomo de elementos y subsistemas cooperantes interconectados de tal manera que se cubren todas las etapas del proceso de producción, desde la planta de manufactura hasta las redes logísticas.

Sobre los principios de diseño en la I4.0 se toma como referente en trabajo realizado por Hermann, M. Pentek, T., & Otto B., [25], los cuales fueron sintetizados la Fig. 1.

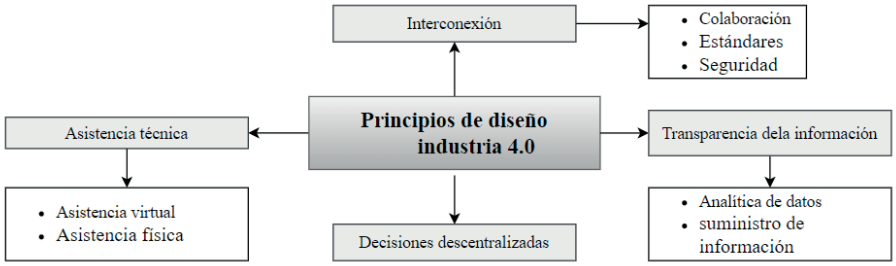


Fig. 1 Principios de diseño de la industria 4.0. Fuente: [25]

En el siguiente apartado se profundiza sobre la flexibilidad (que para el caso presenta un alto grado de sinonimia con el concepto de adaptabilidad y capacidad de respuesta), en el marco de la I4.0.

2.2 Flexibilidad de los sistemas de manufactura en la industria 4.0

En el diccionario de Cambridge se define flexibilidad como la capacidad de cambiar o ser cambiado fácilmente según la situación [26]; dentro de sus sinónimos se encuentran adaptabilidad y modificabilidad. El termino adaptabilidad está definido como la capacidad o la voluntad de cambiar para adaptarse a diferentes condiciones [27].

La necesidad que tienen los sistemas de producción de adaptarse a los requerimientos de mercados sin incurrir en costos excesivos ni gastar una cantidad excesiva de recursos [15], ha dado continua e incremental relevancia a aquellas estrategias que bajo conceptos y principios como flexibilidad, adaptabilidad, reconfigurabilidad, evolución de la arquitectura de control y toma de decisiones ágiles, propenden por mejorar en los sistemas de manufactura la capacidad de adaptación.

Se han estudiado aspectos como el balance entre la flexibilidad y la eficiencia y la importancia de tener entendimiento común en la I4.0 (grado semántico) entre las partes que intervienen [28]; se han investigado y evaluado diferentes formas de flexibilidad [15, 16, 29–31], se ha estudiado la adaptabilidad desde componentes o elementos de la I4.0 como el Cloud Computing, el IoT, Smart Factory [20, 32, 33].

2.3 Relaciones entre los sistemas de apoyo a la toma de decisiones y la industria 4.0

Los Sistemas de Soporte de Toma de Decisiones, DSS (*Decision Support Systems*), son modelos y aplicaciones informáticos para facilitar la toma de decisiones de negocio en la gestión, operaciones y planificación de las organizaciones [30] [34]. Uno de los beneficios de los CPPS, es la posibilidad de conectar directamente sensores y actuadores en la planta de producción con un sistema de toma de decisiones de alto nivel [19]. Esto permite proveer datos en tiempo real al DSS que permiten al sistema productivo reaccionar rápidamente ante eventos imprevistos [19].

Los desarrollos actuales y las tendencias futuras en DSS para la gestión de la manufactura y la cadena de abastecimiento se basan en los CPS [35, 36]. El rápido aumento de la analítica empresarial brinda oportunidades para la investigación de operaciones para resolver tanto problemas de optimización de alta complejidad y gran escala y / o incertidumbre y naturaleza estocástica, como problemas emergentes en la cadena de suministro y la gestión de operaciones [35].

3 Propuesta y desarrollo metodológico

Se llevó a cabo una revisión sistemática de la literatura con el objetivo de consolidar y analizar (desde el punto de vista bibliométrico), documentos presentes en la literatura científica (en general artículos y memorias de congresos), en los que se estudian, analizan o proponen estrategias para aprovechar las tecnologías de la I4.0 en la mejora de la adaptabilidad en los sistemas de fabricación. Lo anterior para proponer las categorías y los niveles bajo las que se podrían clasificar tales estrategias. Esto sirve como punto de partida para su posterior evaluación y favorecimiento de la toma de decisiones.
En este estudio primero se hace un análisis de coocurrencias, a partir del cual se identifican documentos relevantes en la literatura para el establecimiento de categorías a proponer.

3.1 Análisis bibliométrico

El análisis bibliométrico se desarrolló siguiendo las etapas sintetizadas en la Fig. 2, para esto se tomó como base lo presentado en la sección de referentes donde se encontraron algunos elementos comunes que dan insumos para esta revisión.

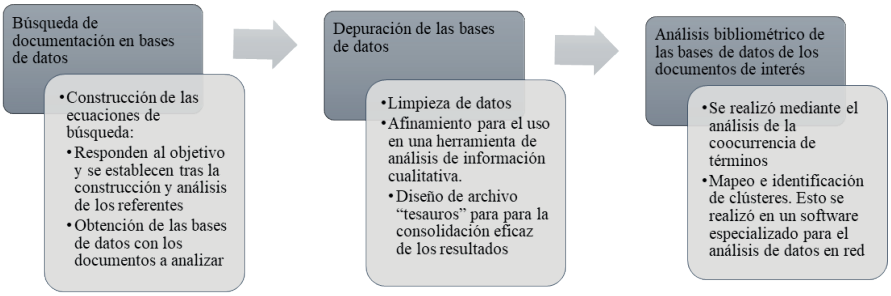


Fig. 2 Etapas del análisis bibliométrico

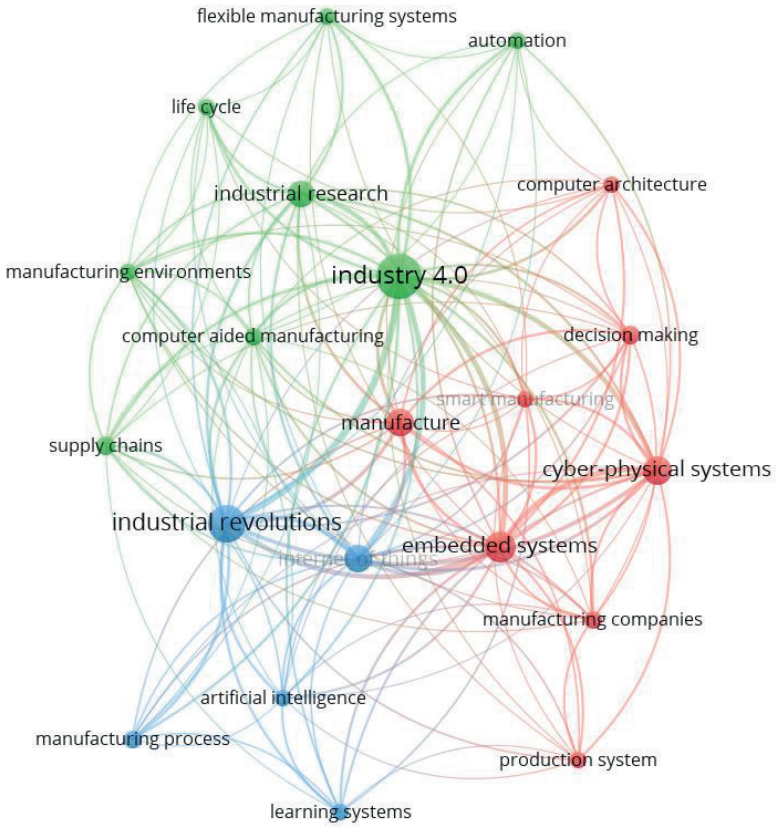
Búsqueda y depuración de documentos en bases de datos. La búsqueda se hizo en la base de datos SCOPUS. En la Tabla 1 se indican algunas de las ecuaciones de búsqueda usadas, en las observaciones se señalan los campos de búsqueda y cantidad de documentos obtenidos tras la depuración la información. Se presentan las ecuaciones

usadas más representativas tras un proceso de tamizaje y para la cuales se presentará el análisis de coocurrencias.

Tabla 1. Ecuaciones de búsqueda

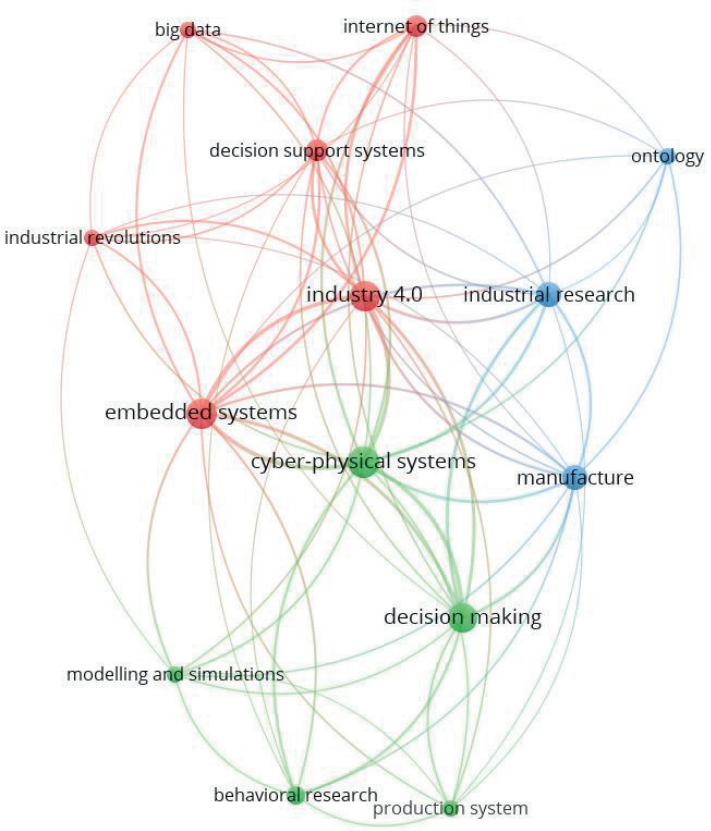
No.	Ecuación de búsqueda	Observaciones
1.	(adaptability OR flexibility OR adaptive AND manufacturing OR reconfigurability OR reconfigurable) AND (manufacturing AND systems OR production AND systems) AND (industry 4.0 OR forth AND industrial AND revolution OR industrie 4.0)	Campos de búsqueda: título, resumen y palabras clave. Documentos encontrados 75
2.	(cyber-physical AND systems OR cyber-physical AND production AND systems) AND (manufacturing AND systems OR production AND systems) AND (industry 4.0 OR forth AND industrial AND revolution OR industrie 4.0) AND (decision AND support AND systems)	Campos de búsqueda: título y palabras clave Documentos encontrados 21
3.	(Industry 4.0 OR Industrie 4.0) AND (manufacturing systems OR Production systems) AND (adaptability OR flexibility OR Reconfigurability OR agility)	Campos de búsqueda: título y palabras clave Documentos encontrados 19

Análisis bibliométrico (análisis de coocurrencias). Se ejecutó un análisis de coocurrencia de términos en VOSViwer, mediante la generación de mapas (redes) de datos (palabras clave), con coocurrencia para los documentos analizados. Los resultados obtenidos se muestran en las figuras Fig. 3 a Fig. 5. En el pie de cada figura se indican los parámetros para la generación del mapa y la cantidad de enlaces resultantes.



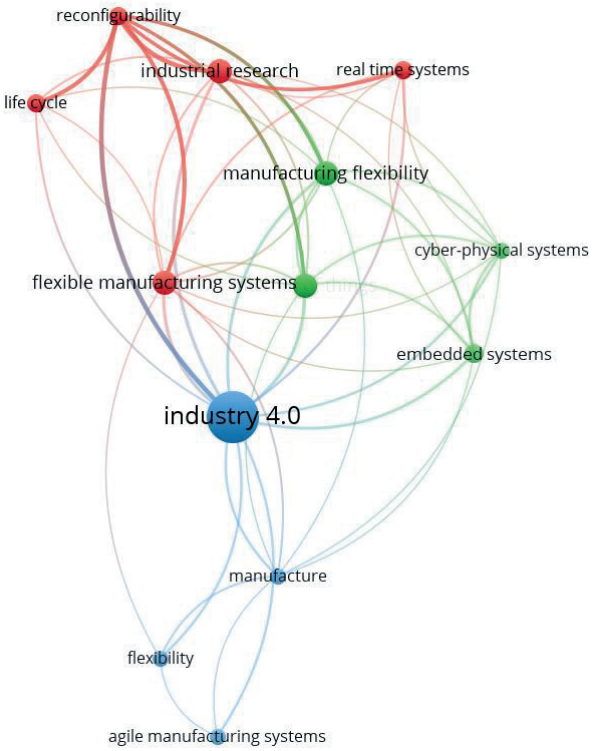
Parámetros para la generación del mapa
Palabras clave: de autor ☐ de indexación ☐ todas ☒
Mínimo de coocurrencias: 5
Enlaces resultantes: 150

Fig. 3 Mapa de coocurrencias, ecuación de búsqueda 1



Parámetros para la generación del mapa
Palabras clave: de autor ☐ de indexación ☐ todas ☒
Mínimo de coocurrencias: 4
Enlaces resultantes: 71

Fig. 4 Mapa de coocurrencias, ecuación de búsqueda 2



Parámetros para la generación del mapa
Palabras clave: de autor ☐ de indexación ☐ todas ☒
Mínimo de coocurrencias: 3
Enlaces resultantes: 103

Fig. 5 Mapa de coocurrencias, ecuación de búsqueda 3

En síntesis, el análisis de coocurrencias nos da evidencias de las interrelaciones que existen entre los términos de búsqueda y la frecuencia con la que aparecen (en cada mapa el tamaño de los nodos está directamente relacionado con la cantidad de documentos que contienen en término en los campos de búsqueda indicados), los arcos se generan a partir del "mínimo de coocurrencias" que fue parametrizado, los colores ilustran la existencia de clústeres de documentos.

Análisis de documentos relevantes para el establecimiento de categorías. Tras revisar aquellos artículos en los que la coocurrencia de términos resultó más relevante para el cumplimiento de nuestro objetivo, y que nos permitieran establecer las categorías y niveles por proponer, se genera el resultado mostrada en la Tabla 2, donde se sintetizan las categorías propuestas y los niveles que podrían tomar acorde con la revisión bibliométrica realizada, en la columna de referente se indican las fuentes que soportan lo propuesto y que también sirven de referente para profundizar sobre los niveles planteados en cada categoría.

Tabla 2. Categorías propuestas y sus referentes

Categoría	Posibles niveles	Ref.
Objetivo de flexibilidad	Incrementar la agilidad	[18],[15]
	Compensar variabilidades temporales	[18]
	Hacer frente a riesgos de interrupción	[16]
	Hacer frente a riesgos de efecto dominó	[16], [39]
	Mejorar la sostenibilidad	[16], [38]
	Integrar proveedores	[16]
Nivel en la ingeniería del proceso	Diseño del producto	[18],[41]
	Planeación de la producción	[18],[42],[43]
	Planeación del servicio	[18]
Nivel en el proceso de manufactura	Gestión de manufactura	[50],[51],[52]
	Control de procesos	[48],[35],[43]
	Control de producción	[42],[48],[23],[49]
	Piso de planta	[44],[45],[46],[3],[47]
Tecnologías requeridas	IoT	[18],[21]
	IA	[18],[51],[54]
	Cloud Computing	[47],[8],[21], [54]
	RFID	[35],[21]
	Blockchain	[51],[35]
Eslabones de la cadena de abastecimiento involucrados	Proveedores	[39],[37]
	Fábrica	[39],[55],[56]
	Distribuidores	[39]
	Minoristas	[39]

A manera de ejemplo, la estrategia a seguir para definir la denominación de la categoría "objetivo de flexibilidad" así como sus niveles, fue el análisis de aquellos documentos en los que términos clave como "flexibilidad" se presentaban con mayor frecuencia, documentos que a su vez presentaban alta coocurrencia de términos con otros aspectos incluidos en la categorización (como tecnologías requeridas o eslabones de la cadena de abastecimiento involucrados). En particular para esta categoría (objetivo de flexibilidad) el estudio realizado por Ivanov, D., Das A., Choi T-M. [16], sobre los nuevos impulsores de flexibilidad para las operaciones de fabricación, cadena de suministro y servicios, tuvo especial relevancia. En este se mencionan los siguientes aspectos de interés para implementar estrategias de flexibilización: 1) riesgos de interrupción, resiliencia, redundancia y efecto dominó en la cadena de suministro, 2) digitalización, operaciones inteligentes y cadenas de suministro electrónicas, 3) sostenibilidad y capacidad de respuesta, y 4) integración de proveedores y flexibilidad de comportamiento [16]; igualmente plantean que dentro de los tópicos trabajados en los artículos que consideraron dentro de su estudio, están los siguientes: 1) flexibilidad de operaciones con la ayuda de nuevas tecnologías de la información, 2) cadenas de suministro y sistemas de fabricación reconfigurables, 3) flexibilidad de operacio-

nes y análisis de negocios, 4) flexibilidad de operaciones y fabricación aditiva 5) flexibilidad de operaciones y gestión esbelta 5) flexibilidad de operaciones y abastecimiento estratégico 7) flexibilidad, resiliencia y gestión de riesgos 8) flexibilidad en el servicio 9) flexibilidad de la cadena de suministro. Características que sirvieron de referentes para lo propuesto, de manera equivalente se fundamentan las otras categorías y niveles presentados en la en la Tabla 2, en la que como indicamos previamente se señalan los referentes considerados.

4 Conclusión

Partiendo de una revisión bibliométrica fue posible identificar un conjunto de categorías relacionadas con las estrategias que usando elementos de la industria 4.0, propender por mejorar la flexibilidad de los sistemas de producción, con lo que subsecuentemente se favorece el análisis, configuración y elección de estas en concordancia con los objetivos y recursos de una organización.

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Factores que influyen en la adaptación de la Industria 4.0 a la gestión del mantenimiento en las empresas colombianas

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Abstract. El creciente desarrollo tecnológico y su uso constante a nivel mundial en todos los procesos industriales, ha permitido a las compañías mejorar en gran medida su eficiencia en todos sus procesos de producción. El mantenimiento industrial está involucrado directamente en estos cambios y debe responder con efectividad a los requerimientos que surgen en la implementación de la Industria 4.0 en las empresas. El mantenimiento puede aportar en gran medida a mejorar la eficiencia de la producción de las empresas, si se planifica y ejecuta aprovechando todos los beneficios de la tecnología en la actual era digital. La industria colombiana está en camino a ser más competitiva en varios sectores económicos. Por lo anterior es necesario identificar los factores más relevantes al momento de adoptar tecnologías de la industria 4.0 usadas en la gestión del mantenimiento que contribuyen en la mejora continua de los procesos industriales del país haciéndolos más eficientes. Esta investigación se centró en el estudio de la adaptación de estas tecnologías y se llevó a cabo mediante un estudio de carácter cualitativo que empleo un muestreo discriminado. Los datos objeto de análisis fueron adquiridos por medio de entrevistas semiestructuradas realizadas a expertos con gran experiencia en la gestión del mantenimiento en Colombia. Los resultados obtenidos destacan la importancia del talento humano y la cultura organizacional en la gestión del cambio en las empresas y como las tecnologías de la Industria 4.0 benefician la ejecución de las tareas de mantenimiento.

Keywords: Gestión del mantenimiento, Industria 4.0, Eficiencia organizacional, Toma de decisiones, cultura organizacional.

1 Introducción

El creciente desarrollo tecnológico y su uso constante a nivel mundial en todos los procesos industriales, ha permitido a las compañías mejorar en gran medida su eficiencia

en todos sus procesos de producción [1]. Esta eficiencia se genera gracias a los tiempos cortos de respuesta a la demanda que generan las actuales economías aceleradas del mundo [2]. El mantenimiento industrial está involucrado directamente en estos cambios y debe responder con efectividad los a requerimientos que surgen en la implementación de la Industria 4.0 en las empresas [3].

La Industria 4.0 encuentra su aplicación en mantenimiento en el diseño de sistemas de autoaprendizaje inteligentes que ayudan a predecir fallos, diagnosticar y activar los programas de mantenimiento [4]. Para extraer información específica y relevante, estos sistemas inteligentes son muy demandados por el acceso a los datos, por su calidad y también por el uso de múltiples fuentes de datos [5]. La Industria 4.0 promueve la conexión de elementos físicos como sensores, computadoras, dispositivos móviles entre otro por medio de Internet [6]. En el marco de la evolución industrial el mantenimiento ha dado respuesta a las necesidades que la producción masiva con altos estándares de calidad ha generado a lo largo del tiempo. Es por esto que frente a cada revolución que ha existido, el mantenimiento ha tenido las siguientes características que lo definieron [7] (ver fig. 1).

Para que un país como Colombia pueda seguir siendo competitivo frente a otros países latinoamericanos, es necesario identificar los factores más relevantes al momento de adoptar tecnologías de la industria 4.0 usadas en la gestión del mantenimiento que contribuyan en la mejora continua de los procesos industriales del país haciéndolos más eficientes. El mantenimiento puede aportar en gran medida a mejorar la eficiencia de la producción de las empresas, si se planifica y ejecuta aprovechando todos los beneficios de la tecnología en la actual era digital. El mantenimiento es de gran importancia en la industria, ya que es el encargado de mantener los activos de una empresa cumpliendo la función para la que fueron diseñados [8]. En Colombia la productividad de la industria se ve afectada en un 8.1% por la gestión del mantenimiento y las paradas no programadas [9].

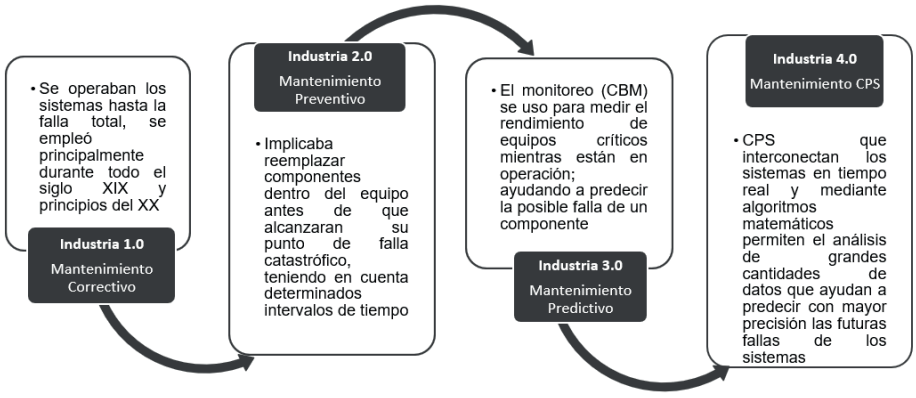

Fig. 1. Evolución del Mantenimiento en la Industria [7].

2 Tecnologías de la Industria 4.0 en el mantenimiento

Adaptar la Industria 4.0 en la gestión de mantenimiento lleva implícito el avance hacia la transformación digital, mediante el uso de las nuevas Tecnologías de la Información y la Comunicación (TIC) [10]. Esta adaptación permite la integración de los sistemas físicos con los virtuales, tales como: Internet de las Cosas (IoT), Big Data, Inteligencia Artificial (AI), Sistemas Ciber Físicos (CPS), ciberseguridad, entre otros [11]. La adaptación unida de estos sistemas contribuyen a la revolución del mantenimiento, pasando de una ejecución de mantenimientos correctivos [12] y preventivos [13], hacia la ejecución de un mantenimiento predictivo, a través de algoritmos diseñados que permiten autodiagnósticos y las auto reparaciones, basados en la información recopilada por medio de sensores en tiempo real, en escenarios que permiten almacenamiento masivo de datos para su análisis exhaustivo, permitiendo de esta manera predecir las futuras fallas en los sistemas.

2.1 Tecnologías de la Industria 4.0 en Colombia

Los empresarios colombianos cada vez más están adoptando estrategias para migrar sus negocios de un modelo tradicional a modelos fundamentalmente digitales y eso se evidencia en la cantidad de empresas que conocen que es la Industria 4.0. Para el año 2019 88,2 % de empresas en Colombia ya conocían la Industria 4.0, en comparación al 2016 donde tan solo el 43,7 % de las empresas tenían conocimiento sobre este tema (ver fig. 2) [14].

El mantenimiento representado en las paradas no programadas ocupa el cuarto lugar en la pérdida de productividad en la industria colombiana (ver fig.3) [5].

Las tecnologías asociadas la Industria 4.0 usadas en el mantenimiento, como los son el Internet de las cosas (IoT) han tenido un alto crecimiento, por lo anterior es necesario tomar decisiones en corto tiempo sobre la adaptación de estas tecnologías en el país. Para tomar decisiones primero se debe identificar en que escenarios de desarrollo se encuentra Colombia con respecto a estas tecnologías (ver fig. 4) [15].

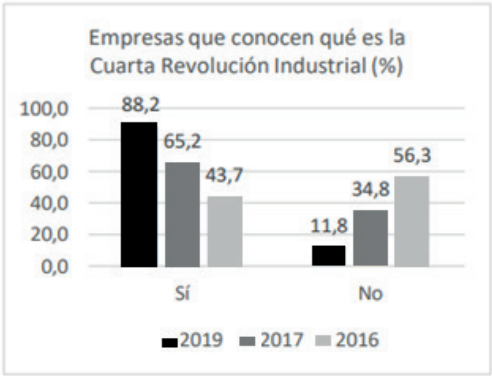

Fig. 2. Empresas que conocen qué es en la cuarta revolución industrial en Colombia [14].

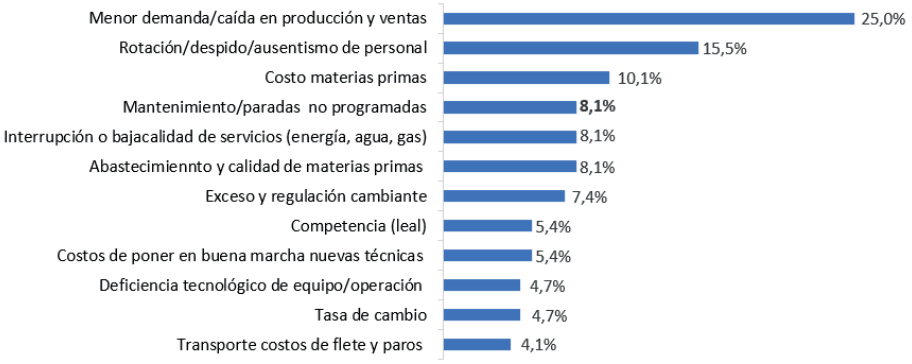

Fig. 3. Factores que han afectado negativamente la productividad en Colombia [5].

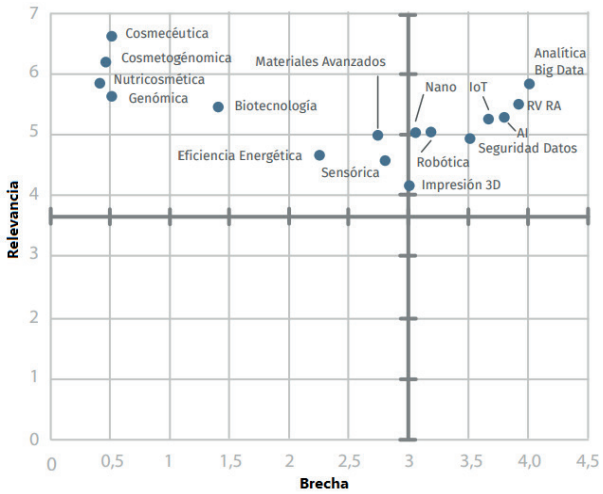

Fig. 4. Matriz de brecha frente a relevancia de las tecnologías en Colombia [15].

3 Metodología de Investigación.

Hay una carencia significativa de procesos de investigación empírica en el campo del mantenimiento. Así lo evidenciaron (Fraser, K. & *et al.* 2015) en [16] cuando revisaron la literatura y encontraron que, de varios miles de artículos sobre los conceptos de mantenimiento más comunes, una pequeña cantidad mostraban evidencia empírica del mundo real [3]. A pesar de ello existen algunas investigaciones empíricas de mantenimiento muy representativas, tales como (McKone, K. E., & *et al.*) en [17] que definieron un marco teórico de Mantenimiento Productivo Total (TPM). Y (Jonsson, P., 2000) en [18] teorizó sobre la importancia de la prevención, la integración del mantenimiento duro y la integración del mantenimiento blando, seguido de la vinculación de taxonomías empíricas de plantas con factores contextuales y diferenciales de rendimiento, por mencionar algunas.

El proceso de investigación del presente trabajo se diseñó como un estudio cualitativo. Este estudio puede ser definido como cualquier tipo de investigación que produce hallazgos a los que no se llega por medio de procedimientos estadísticos u otros medios de cuantificación. Bajo este enfoque pueden tratarse investigaciones sobre funcionamiento organizacional, movimientos sociales, fenómenos culturales o interacciones entre naciones. Tal es el caso del mantenimiento, como un proceso importante dentro de las industrias. En el desarrollo de esta investigación se reunieron datos por medio de entrevistas y observaciones con el propósito de descubrir conceptos y relaciones en los datos brutos y luego organizarlos en un esquema explicativo teórico [19].

Así mismo se hizo un muestreo de acontecimientos o sucesos representativos de conceptos teóricos pertinentes mediante entrevistas semi estructuradas. Luego estas entrevistas fueron comparadas en la búsqueda de propiedades y dimensiones, siempre considerando como un factor principal el rango o variación en la dimensión. Las personas y herramientas tecnológicas utilizadas en este proceso, proporcionaron los medios para obtener estos datos.

Esta investigación se centró en un muestreo discriminado que incluyo 20 sesiones con 8 investigadores y siete (7) entrevistas con expertos industriales que representaban a 6 empresas diferentes. Toda esta investigación se desarrolló en el marco de las medidas de distanciamiento social y el confinamiento en los hogares. Estas medidas han modificado las formas tradicionales que usamos para interactuar con nuestros semejantes, lo cual nos llevó a aprender a realizar nuestro trabajo bajo una autonomía caracterizada por la distancia y la virtualidad, lo anterior debido a la emergencia sanitaria generada por el COVID-19. En este tipo de investigaciones cualitativas, la interacción personal en la etapa de adquisición de datos es de gran importancia, pero el uso de Internet en todas las facetas de nuestra vida nos llevó a comprender que estamos frente una nueva era investigativa [20]. Este trabajo utilizó herramientas digitales y las TIC, bajo con rigurosidad que permitió continuar con la calidad en los procesos de la investigación durante todas las etapas de este.

Por lo anterior se hizo énfasis en la información brindada por los entrevistados en las sesiones virtuales mediante las cuales se realizaron las entrevistas semi estructuradas en las que se mantuvieron encendidas las cámaras de todos los participantes. Los entrevistados nos compartieron presentaciones digitales, nos mostraron softwares usados en la gestión del mantenimiento de sus empresas y las estrategias tecnológicas que emplean en sus labores como expertos en mantenimiento. La entrevista consto de 10 preguntas de base y estuvieron orientadas a identificar las tecnologías de la Industria 4.0 usadas en los procesos de la gestión del mantenimiento en las empresas colombianas. Los 7 expertos en mantenimiento industrial entrevistados tenían más de 10 años de experiencia en la industria, son ingenieros que trabajan en empresas de sectores tales como el alimenticio, educativo, abastecimiento, avícola, tecnológico y petrolero. Las personas que fueron entrevistadas son personas de alto rango dentro de las empresas y son los tomadores de decisiones asociadas al uso de tecnologías en los procesos de mantenimiento.

4 Resultados

4.1 Estructura de datos.

Los datos se estructuraron mediante una codificación selectiva a través de un muestreo discriminado dirigido por la lógica, para este muestreo es importante un cierto grado de consistencia en el sentido de que las comparaciones se realizaron sistemáticamente en cada categoría, sin perder la flexibilidad que puede requerirse en casos inesperados como el COVID-19 que sucedió en el marco del desarrollo de esta investigación. La recolección de datos es guiada por el análisis de la información y este análisis es realizado en paralelo con el muestreo de datos. El propósito de la codificación selectiva fue integrar las categorías de acuerdo con las dimensiones y de esta manera obtener una teoría.

4.2 Muestreo discriminado

Durante el desarrollo del muestreo discriminado, se escogió la plataforma Microsoft Teams como medio virtual para realizar las entrevistas y se seleccionaron 7 expertos en mantenimiento con poder en la toma de decisiones asociadas al uso de tecnologías en los procesos de mantenimiento y se seleccionaron los estudios nacionales asociados al desarrollo tecnológico del país para realizar el análisis comparativo. Lo que guío la recolección de datos durante el muestreo discriminado fueron las preguntas analíticas y las comparaciones sistemáticas. Las preguntas de las entrevistas se basaron en conceptos derivados de la literatura, de la experiencia y trabajo de campo realizado previamente por los investigadores en el desarrollo de visitas técnicas a empresas industriales como parte del proceso formativo. Las entrevistas se realizaron bajo un enfoque menos estructurado, pero tuvo una guía general bajo 10 preguntas rectoras que dieron a los entrevistados más espacio para contestar en términos de lo que es importante para ellos. Se compararon las respuestas que dieron los diferentes entrevistados a esas preguntas.

4.3 Validación de los datos

La validación se realizó simultáneamente en cada paso del análisis y del muestreo, mediante la comparación constante de los resultados del análisis de los datos recolectados en las entrevistas y los datos reales, realizando modificaciones o adiciones a medida que llegan los datos a la investigación, de esta manera se validaban o negaban las interpretaciones realizadas. Sólo los conceptos que cumplen todos los requisitos de este proceso constante y riguroso de comparaciones entran a ser parte de la teoría. El muestreo finalizo al saturar las categorías que surgieron de los datos analizados.

4.4 Categorías

Después de un gran volumen de conceptos recopilados en el muestreo discriminado realizado en el proceso de investigación, se establecieron las siguientes categorías que

definen los factores más relevantes al momento de adoptar tecnologías de la industria 4.0 en la gestión del mantenimiento, que pueden contribuir mejorar los procesos industriales de Colombia haciéndolos más eficientes:

Talento humano

La categoría central que permeo las demás categorías dentro de los factores más relevantes al momento de adoptar las tecnologías 4.0, fue la categoría de talento humano. Esto corroboró la importancia que en la gestión del mantenimiento ha tenido el factor humano para lograr la eficiencia en sus procesos [21]. Uno de los expertos expreso: "Las tecnologías emergentes de la Industria 4.0 son muy buenas y nos podrían beneficiar mucho, pero dentro de la mayoría de las empresas industriales del país, no hay personas calificadas para emplear estas tecnologías en la gestión del mantenimiento". La verdadera fuente de competitividad industrial es el Talento Humano comprometido, que encamina sus esfuerzos en resolver las necesidades de las empresas para alcanzar los objetivos estratégicos [22]. Otro de los expertos describió en este sentido: "El éxito de la gestión de mantenimiento, es un equipo de trabajo que este motivado por sus líderes y que se encuentre en constante capacitación sobre las innovaciones y avances técnicos del mantenimiento y de esta forma mejorar las competencias del personal en los procesos y en este caso, en el uso de estas nuevas tecnologías para mejorar estos procesos y ser más eficientes en las labores que se realizan". Las deficiencias en el sistema de formación del talento humano de una empresa impacta de forma directa en la pérdida de competitividad en la economía, debido a que no se puede aprovechar el potencial económico y técnico de las nuevas tecnologías, si en primer lugar no se realizan los cambios el sistema de capacitación y educación [23], al respecto uno de los expertos expreso: "En Colombia es necesario que las empresas brinden facilidades a sus empleados para seguir mejorando su perfil profesional a través de estudios formales como especializaciones y estudios de educación continua o cursos para certificaciones técnicas". Durante la comparación rigurosa de los datos se definió que el factor más relevante en la adopción de las tecnologías 4.0 en los procesos de mantenimiento en Colombia es el factor humano y es el primero que deberían estudiar y organizar las empresas antes de implementar tecnologías en sus procesos.

Cultura Organizacional

Otro factor relevante en la transformación tecnológica del proceso de mantenimiento en las empresas colombianas; es la cultura organizacional, teniendo en cuenta que para el uso de estas tecnologías 4.0 es necesario realizar cambios a nivel tecnológico y fundamentalmente se necesita realizar cambios en la cultura organizacional que procuren el aprovechamiento de estas herramientas tecnológicas y la vinculación de las mismas a las nuevas estrategias de las organizaciones [24]. Al respecto uno de los expertos afirmo que: "En Colombia no existe una cultura dentro de las empresas que migre de forma rápida de procesos industriales tradicionales a procesos industriales tecnológicos o digitales, en mantenimiento se utilizan ciertas técnicas predictivas que involucran algunas herramientas tecnológicas, pero en su mayoría las tareas de mantenimiento son hechas por colaboradores que culturalmente no están familiarizados con la tecnología

de la industria 4.0". Las empresas tienen grandes desafíos que exigen una cultura del cambio, para poder transformar muchos procesos de gestión como la comunicación, la gestión de la información y procedimientos técnicos con el fin de lograr que los trabajadores puedan manejar la complejidad de los procesos y se conviertan en miembros activos de la innovación y del cambio cultural [22]. Uno de los expertos describió alrededor de este tema que: "Modernizar los procesos de mantenimiento con nuevas tecnologías, no solo se trata de comprar nuevos equipos o softwares, si no de cambiar las formas como se han hecho las tareas de mantenimiento por años. Adicionalmente es enseñar de nuevo a los técnicos, como deben hacer sus labores ahora que serán apoyadas con la tecnología". Las empresas deben definir una nueva estructura y darle la importancia al área digital en la estrategia corporativa [25]. En este sentido uno de los expertos concluyó: "Si los empresarios colombianos que estamos en el área de mantenimiento queremos seguir siendo competitivos, debemos transformar nuestras empresas e ingresar en la era digital, pues es evidente que es en esos escenarios digitales en donde se desarrollaran las tareas más complejas e importantes de nuestra función de mantenedores de activos". Podemos afirmar que en Colombia la gestión de mantenimiento no solo depende de las estrategias de transformación digital que tenga una empresa. Depende fundamentalmente de la cultura organizacional que tienen estas compañías y su resiliencia frente a la gestión del cambio.

Toma de decisiones basada en datos

El uso de tecnología avanzada en mantenimiento permite análisis predictivos y sugiere soluciones factibles, con aplicación principal en la Industria 4.0 y especialmente en aquellos aspectos del mantenimiento que se ocupan de la recolección de datos, su análisis, visualización y la toma de decisiones sobre los activos [26]. Uno de los expertos mencionó al respecto: "Para mejorar la confiabilidad de nuestros sistemas en la empresa hemos diseñado un modelo multi estrategia que permite recopilar datos de varias dependencias de la empresa por medio de una plataforma virtual diseñada para tal fin, que en el departamento de mantenimiento aprovechamos al máximo y así contar con más información para tomar decisiones más asertivas. En la gestión de activos, la extracción de grandes cantidades de datos puede ayudar a descubrir conocimientos en la identificación de nuevas tendencias y fallas, además de identificar por anticipado las situaciones no visibles. El enfoque en grandes volúmenes de datos permite combinar la información contextual en los sistemas de apoyo a las decisiones de mantenimiento [27]. Uno de los expertos expuso: "La revolución de la Industria 4.0, es la revolución del dato y lo que hacemos los mantenedores en Colombia es tomar decisiones con datos que nos dan los mantenimientos predictivos o las inspecciones visuales. Es importante aprovechar estas nuevas tecnologías en la gestión del mantenimiento para seguir en una mejora continua del proceso y ser más eficientes a lo largo del tiempo". Para apoyar un proceso eficaz de adopción de decisiones en materia de mantenimiento se necesita un sistema de apoyo a las decisiones basado en la adquisición de datos que permita la gestión de estos [4]. Uno de los expertos concluyó al respecto: "En nuestra empresa fue necesario transformar la forma de gestionar los datos en menor tiempo, hacerlo en la medida de lo posible en tiempo real, cuando migramos a una plataforma digital, pudimos visualizar nuestros datos de mantenimiento en menos tiempo y en mayor cantidad,

de esta manera adaptamos nuestros planes de mantenimiento de acuerdo con la evidencia encontrada y en muy poco tiempo nuestros indicadores de gestión mejoraron considerablemente". De los anterior podemos concluir que en la gestión del mantenimiento la toma de decisiones basada en datos es algo que ha evolucionado a lo largo del tiempo y que el avance tecnológico permite tomar decisiones apoyadas en más datos, aumentando de esta manera el nivel de confiablidad de estas decisiones.

Tecnologías 4.0 en el mantenimiento

Una técnica tradicional de mantenimiento es observar los datos proporcionados por uno, o una serie de sensores, el Machine Learning dota a los equipos de mantenimiento de herramientas de aprendizaje de máquina capaces de adaptarse a las condiciones de funcionamiento, incluso aquellas que cambian rápidamente [28]. Uno de los expertos explicó: "El Machine Learning es una de las tecnologías de la Industria 4.0 que más impacta al mantenimiento permitiéndole ser más eficiente en sus procesos para el diseño de planes de mantenimiento efectivo, los algoritmos que podemos diseñar nos permiten analizar más variables para tomar las decisiones de intervención de los activos de la empresa". La tecnología del Big Data potencializa la recopilación de datos e información de diferentes fuentes y la recolección de datos, para analizarlos a fin de extraer información y conocimiento; y la extracción y visualización de información, para apoyar la decisión de mantenimiento [4]. Uno de los expertos menciono que: "Empleamos el Big Data en nuestros procesos y lo hicimos debido al gran volumen de datos que captamod en nuestras maquinas, esto permitió que pudiéramos ver la información prácticamente en tiempo real, detectando fallas en los equipos y hemos realizado intervenciones a tiempo, antes de que ocurriera una falla que nos retrasara de alguna manera la producción". La computación en la nube es un modelo que ayuda a mantener y almacenar grandes depósitos de datos en un almacén central y proporciona al usuario una interfaz para llevar a cabo una herramienta de análisis poderosa y robusta simplemente por su capacidad de integrar varios insumos de mantenimiento, disposición, condiciones, clima, inventario, entre otras [4]. Uno de los expertos aseguro que: "La computación en la nube fue la herramienta que empleamos en la plataforma de análisis de mantenimiento que diseñamos como un desarrollo propio adaptado a las necesidades de nuestra empresa para almacenar y analizar los datos que obtenemos de los procesos de mantenimiento, esta herramienta se diseñó para que su uso fuera intuitivo y fácil para nuestros técnicos, que no cuentan con mucha experiencia en el uso de herramientas informáticas para el reporte de sus actividades". Después de un análisis exhaustivo de la información recopilada en la investigación realizada, las tecnologías que más beneficios han brindado al mantenimiento industrial en Colombia son el Machine Learning, el Big Data y la Computación en la nube

5 Conclusiones

Realizar un estudio cualitativo alrededor de la gestión de mantenimiento y la industria 4.0 y su uso en Colombia nos ha permitido ver y dimensionar un amplio panorama de desarrollo del país alrededor de estos temas, en donde la oportunidad de innovar en el

desarrollo e implementación de las tecnologías asociadas a la Industria 4.0 son de gran importancia en el desarrollo económico y competitivo del país. La investigación mostro que los cambios que se requieren hacer dentro de las organizaciones para adoptar estas tecnologías, no solo implican un nivel tecnológico, sino que es fundamental en primera medida adaptar el talento humano de las empresas colombianas.

Se determinó que la gestión del mantenimiento es una de las áreas de las empresas que puede implementar en sus procesos las tecnologías emergentes asociadas a la industria 4.0 y encontrar beneficios sustanciales que se pueden traducir en eficiencias presupuestales, brindado a las empresas que utilizan estas tecnologías seguir siendo competitivas en el mercado. Se definió que la toma de decisiones es el proceso que más impacto tiene con el uso de estas tecnologías en el mantenimiento, ya que estas decisiones pueden tomarse con un mayor nivel de confiabilidad y contribuir a lograr los objetivos de las estrategias organizacionales de la industria en Colombia.

De los datos analizados en la presente investigación se encontró que, aunque en Colombia se conocen estas tecnologías y sus beneficios al emplearlas en los procesos de mantenimiento, la mayoría de las empresas no cuenta con personal capacitado para el uso de estas tecnologías y aun no son empleadas en sus procesos de producción incluyendo la gestión del mantenimiento. El panorama futuro que se vislumbra en la industria colombiana es uno en el que las empresas lideren estos procesos de cambio, tanto cultural como de talento humano dentro de sus compañías, adaptando a sus necesidades de capacidad humana y tecnológica el uso de herramientas como el Big Data, Machine Learning, computación en la nube entre otras, que beneficien sus procesos y los hagan eficientes permitiéndoles seguir siendo competitivos en este nuevo mundo digital.

Se proponen futuras investigaciones en torno alrededor de este tema que permitan caracterizar las tecnologías de la industria 4.0 desde sus beneficios técnicos y desde la monetización que estos beneficios representan para las empresas que tienen una estrategia de transformación digital en sus procesos de producción.

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Desarrollo de herramientas de soporte a la toma de decisiones en una planta de producción de jugos concentrados

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Resumen. En este trabajo se describe el desarrollo de una herramienta de asistencia a la toma de decisiones para la operación de la planta de jugos concentrados de manzana y pera de la empresa Jugos S.A. El objetivo de la herramienta es generar un programa detallado de los lotes de jugo clarificado a producir en las próximas semanas a partir de pronósticos de ingreso de fruta, compromisos comerciales y restricciones de infraestructura. La herramienta se basa en dos módulos interactivos, PLANNER y SIMOPT con propósitos diferentes y complementarios. Cada módulo está basado en modelos mixto-enteros con interfaces para ingreso de datos y visualización de resultados. PLANNER a su vez consiste de tres submódulos. SIMOPT proporciona la condición operativa de la planta junto con el cálculo de costos específicos. Esta información es a su vez empleada por PLANNER para evaluar las correspondientes funciones objetivo económicas. Además de proveer condiciones operativas óptimas para la planta y programas de producción factibles, las herramientas desarrolladas permiten generar guías para la producción futura y realizar estudios de escenario.

Palabras Clave: Jugo Concentrado de Fruta, Toma de Decisiones, *Scheduling* de Lotes, Planeamiento de la Producción, MINLP.

1 Introducción

La Cadena de Suministro de la Industria de la Fruta (CSIF) de pepita es un sistema complejo que involucra varios actores: chacras de producción de peras y manzanas, galpones de empaque, plantas de elaboración de jugo concentrado, cámaras frigoríficas y empresas de transporte. Todo el sistema está impulsado por la disponibilidad de fruta en cada temporada con el objetivo de producir una enorme cantidad de productos: manzanas y peras frescas en diferentes empaques y jugo concentrado de manzana y pera de variada acidez en una amplia variedad de envases. Una cualidad distintiva de este sistema y que torna la toma de decisiones una actividad sumamente desafiante es la

significativa incertidumbre existente en ambos extremos de la cadena: disponibilidad de fruta en chacras y precios y demandas internacionales de los productos. Aunque la mayoría de las empresas de la CSIF en la Argentina incorporaron mucha innovación tecnológica en los últimos veinte años (equipamiento, automatización, monitoreo y control) para competir a estándares internacionales, la toma de decisiones permanece aún como una actividad predominantemente artesanal, basada en la experiencia e intuición de los gerentes y asistida, como mucho, con planillas de cálculo. No obstante, el sistema frutícola nacional ha sido sumamente estudiado a nivel académico en la última década. Por ejemplo, la CSIF de pepita ha sido a modelada en [1, 2 y 3] con foco en la optimización del planeamiento de la producción desde el punto de vista de una compañía que opera varios nodos a lo largo de la cadena. Además, modelos de planeamiento específicos fueron propuestos para la mayoría de los segmentos más importantes: chacras de frutales [4], galpones de empaque [5] y plantas de jugo [6].

Este proyecto de enfoca en el nodo de producción de jugo concentrado de la cadena. Las plantas de jugo en Argentina producen jugo clarificado a 70°Brix, la mayoría del cual se destina al mercado internacional. Argentina posee el 5% del mercado internacional de jugos concentrados. Jugos S.A. es el mayor productor de jugo concentrado de manzana y pera en Argentina con aproximadamente el 60% de la producción nacional, de la cual el 70% se exporta y el resto se consume localmente. En el año 2013 la gerencia de la empresa Jugos S.A. decidió emprender el desarrollo de herramientas de apoyo a la toma de decisiones basadas en modelos matemáticos para asistir a los ingenieros de la planta en el proceso de toma de decisiones tácticas y operativas, reconociendo el valor de contar con herramientas automáticas para realizar análisis de costos, el planeamiento de la producción y generar estudios de escenario. En este artículo comentamos los aspectos más relevantes de este proyecto.

2 Proceso de Producción de Jugo Concentrado

El jugo clarificado de pera/manzana se comercializa típicamente como concentrado de 70-75 °Brix siendo un producto muy estable que puede ser almacenado y transportado de manera segura y económica. El parámetro característico del jugo concentrado es la acidez total expresada como porcentaje de ácido málico, que fluctúa típicamente entre 1.0 y 3.0 % para jugo de manzana y entre 1.0 y 2.0% para jugo de pera.

En la Fig. 1 se muestra un esquema general del proceso de producción de jugo clarificado. La producción de jugo semielaborado involucra las siguientes etapas: lavado, molienda, extracción por prensado, separación pulpa-orujo, maceración y concentración. La producción de jugo clarificado involucra adicionalmente, dilución (si se reprocesa jugo semielaborado), filtración, concentración final, empaque y almacenamiento refrigerado. Para una descripción detallada del proceso consultar [7]. Las plantas modernas también cuentan con varias líneas de producción paralelas, cada una de las cuales se puede dedicar a un tipo de jugo particular. Esto permite el procesamiento de un solo tipo de fruta a gran capacidad (pera o manzana) o ambas simultáneamente, cada una en alguna de las líneas disponibles.

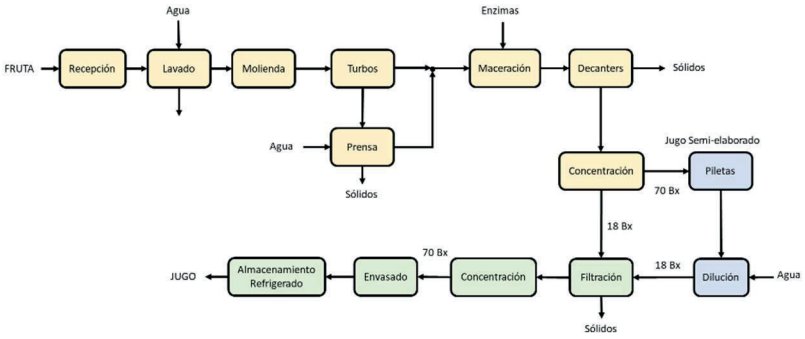


Fig. 1. Proceso típico de producción de jugo de fruta.

3 Proceso y Operación en Jugos S.A.

Jugos S.A. posee una planta de producción de jugos concentrado en Villa Regina, Río Negro, Argentina. La Fig. 2 ilustra el diagrama de flujo principal del proceso. A grandes rasgos, existen dos líneas de procesamiento en la planta: la primera (parte superior del diagrama) está destinada a la producción de jugo clarificado, mientras que la otra (parte inferior del diagrama) produce jugo semielaborado para ser almacenado en piletas. La primera parte del proceso es una playa de recepción abierta donde la fruta se almacena en bines, con dispositivos hidráulicos (lagares) para alimentar a los molinos. Luego de lavar y moler la fruta, la pulpa es separada en una serie de filtros centrífugos (turbos) y prensas.

A continuación, la pulpa es tratada con enzimas para extraer el jugo remanente en la membrana celular. Luego se realiza una separación adicional de líquido y sólidos en una serie de equipos llamados *decanters*. El jugo obtenido se concentra luego con evaporadores multi-efecto. En la línea de jugo semielaborado el jugo se concentra hasta 70° Brix y se almacena en piletas grandes para su posterior reprocesamiento. En la línea de jugo clarificado se realiza una preconcentración (18°Brix) antes de que el jugo se pase por una etapa de ultrafiltración. Finalmente, el jugo se concentra hasta (70°Brix) previo a su envasado y almacenamiento en frío. Cuando es necesario se toma jugo semielaborado desde las piletas de almacenamiento y se diluye con agua antes de ser reprocesado (ultrafiltración, concentración, empaque y almacenamiento).

La planta posee varias calderas para suministrar vapor a los evaporadores multi-efecto y cubrir otros requisitos de calentamiento. El agua extraída del jugo en la etapa de concentración es recolectada y utilizada en otros sectores del proceso (hidratación, lavado de la fruta). También se emplea agua de pozo, previo ablandamiento en una planta de ósmosis para su uso en la producción de vapor en las calderas y para refrigeración en condensadores y otros intercambiadores de calor. El agua que se emplea para transportar la fruta en los lagares se somete a un tratamiento biológico en piletas para ajustar la DBO y otros parámetros de calidad antes de su disposición final [8].

La planta utiliza grandes cantidades de gas natural en las calderas y de energía eléctrica para los equipos de bombeo, separación y refrigeración.

Los sólidos extraídos en las diferentes etapas de separación (turbos, prensas, *decanters* y filtros) son recolectados y destinados a la elaboración de compost.

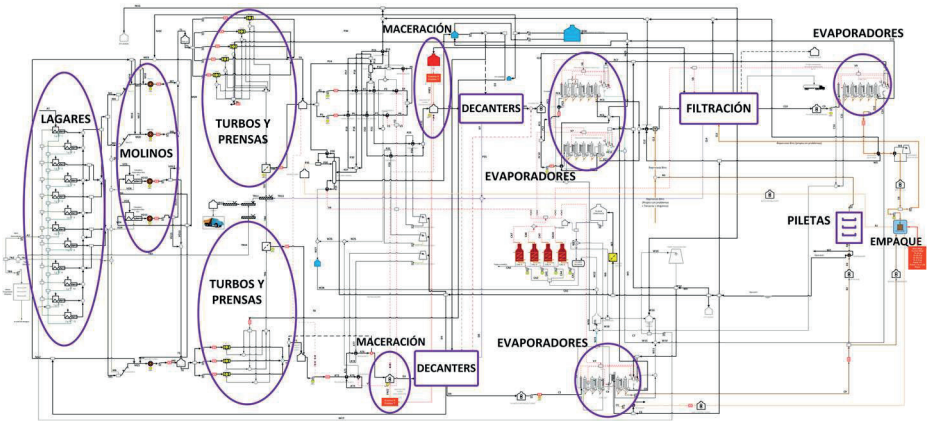


Fig. 2. Diagrama de flujo de la planta de Jugos S.A.

La planta es bastante flexible y, si es necesario, permite compartir equipos entre las líneas de producción previa limpieza y desinfección. De hecho, existen varias interconexiones entre las líneas en varios puntos a lo largo del proceso, lo que permite incrementar la capacidad de producción de una línea con recursos de la otra si es necesario. Se dispone de sistemas *Clean-in-Place* (CIP) para acondicionar los equipos cada vez que se producen estas maniobras.

Aunque muchos de los subprocesos son en realidad operaciones *batch*, la planta puede operarse prácticamente como un sistema continuo durante periodos prolongados. Las diferentes variedades de fruta almacenada en la playa de recepción se vuelcan de los bines a los lagares mediante auto-elevadores. Si bien ésta es claramente una operación *batch*, la gran cantidad de material que puede acumularse en los lagares hace que la alimentación a los molinos resulte virtualmente continua. Adicionalmente, la etapa de maceración requiere el contacto de la pulpa con enzimas durante un cierto periodo, operación que tiene lugar en tanques de grandes dimensiones. Con el objetivo de operar de manera continua, existen varios tanques dedicados a esta operación, tal que uno de ellos siempre está alimentando al proceso, mientras los restantes están siendo llenados o realizando la maceración. De manera similar, la ultrafiltración también es un proceso discontinuo dado que las membranas se van ensuciando y los filtros deben ser sacados de operación con alguna frecuencia para proceder a su limpieza [8]. Por esta razón, la ultrafiltración se realiza en varios filtros paralelos tal que algunos se encuentran funcionando mientras otros se limpian para recuperar eficiencia. Varios tanques *buffer* a lo largo de todo el proceso aseguran la operación continua de equipos como turbos, prensas, *decanters* y evaporadores por periodos extensos. En conclusión, aunque muchos equipos y subprocesos son *batch*, para muchos propósitos operativos (y de modelado matemático), la planta puede ser considerada como un proceso continuo.

Cabe aclarar que existen especificaciones de calidad muy estrictas para los jugos de manzana y pera. En particular, todos los equipos deben ser cuidadosamente lavados por

el sistema CIP con cierta frecuencia y cada vez que hay un cambio en el tipo de fruta en la línea de producción. Estas operaciones de limpieza requieren mano de obra intensiva y demoran varias horas durante las cuales la línea no está operativa.

Adicionalmente, un recurso logístico muy importante del proceso es el sistema de piletas de jugo semielaborado. La planta posee varias piletas de grandes dimensiones especialmente acondicionadas para el almacenamiento de jugo no clarificado. Este jugo puede ser bombeado desde el proceso a las piletas o desde las piletas al proceso cuando resulte necesario. Cada pileta almacena un tipo específico de jugo, pera o manzana, en rangos específicos de acidez. Se debe realizar una limpieza cada vez que una pileta se vacía y se llena con jugo de la otra fruta. Además de almacenar jugos de las diferentes especies, las piletas también cumplen la función de preservar jugos de cierta especificación. Por ejemplo, típicamente, el jugo de manzanas ácidas no se mezcla con jugos de manzanas poco ácidas. De esta manera la acidez se preserva y puede ser utilizada para ajustar la especificación de lotes futuros.

La operación final es el envasado, proceso en el cual recipientes de cierto tipo se llenan de manera secuencial. Los envases más comúnmente utilizados son bines con bolsas de polietileno y tambores plásticos o metálicos. El jugo envasado se almacena en cámaras frigoríficas antes de ser despachado. La planta posee una cámara de gran dimensión, pero si es necesario la empresa puede contratar capacidad de frío de terceros proveedores.

Respecto de la mano de obra, la planta posee un turno de personal estable para realizar actividades de producción y mantenimiento. En periodos de ingresos de fruta elevados o de grandes volúmenes de jugo semielaborado, se trabaja en tres turnos para lo que se requiere la contratación de personal adicional. Finalmente, aparte de las fluctuantes disponibilidad de fruta y demanda de jugo, el proceso/negocio está sujeto a otras restricciones. Típicamente suele haber restricciones de disponibilidad de gas natural durante los meses fríos y de energía eléctrica en verano. En estos periodos la empresa debe optar por interrumpir la producción o enfrentar penalidad en los precios de estos servicios. En la Tabla 1 se presenta un detalle de los principales parámetros de la planta para dar un panorama de la magnitud del proceso.

Tabla 1. Datos de la Planta.

Capacidad de producción (gal/año)	6 000 000
Capacidad de molienda (ton/día)	1 800
Capacidad de almacenamiento en frío (gal)	1 800 000
Superficie del *site* (m^2)	6 700
Laguna de tratamiento de efluentes (hectáreas)	6
Empleados (máxima capacidad)	175

A grandes rasgos se puede decir que la producción esta dictada por las órdenes de compra que realizan los clientes a lo largo del año de los diferentes tipos de jugos, las cuales difieren básicamente en volúmenes, acidez y tipos de envase. Durante la temporada de cosecha (febrero a abril) la fruta que ingresa típicamente sobrepasa la cantidad necesaria para elaborar las órdenes existentes. En este caso se produce y almacena jugo

semielaborado. En paralelo, con el objetivo de evitar una acumulación excesiva de fruta en la playa de recepción, también se elaboran y almacenan en frío lotes de jugo clarificado de calidades estándar, ya sea para atender directamente ordenes futuras o para reprocesar para elaborar nuevas órdenes. El problema de planeamiento de la producción básicamente requiere definir el tipo de fruta a procesar cada día en cada línea para satisfacer en tiempo y forma las órdenes de los clientes, operando dentro de las capacidades de producción y almacenamiento disponibles.

Cabe mencionar que la empresa Jugos S.A. posee las siguientes certificaciones de producción: FSSC 22000 (ISO 22000, ISO/TS 22002-1 y adicionales), producción orgánica, programas NOP-Canadá, Arg.-UE, IFOAM, MAFF, Kosher, miembro "B" de SEDEX.

4 Organización del Proyecto

En este contexto de gran incertidumbre, el desafío reside en decidir qué productos elaborar cada día del horizonte de planeamiento con el fin de maximizar el beneficio de la empresa a lo largo del ciclo comercial. Para automatizar este complejo y artesanal problema de toma de decisiones, los ingenieros de procesos de la compañía junto con nuestro grupo de investigación conformamos un equipo para desarrollar un Sistema de Soporte a las Decisiones (SSD) basado en modelos matemáticos. El proyecto se organizó en un esquema de cuatro etapas:

1. Recopilación de datos del proceso
2. Desarrollo del módulo de simulación/optimización
3. Desarrollo del módulo de planeamiento de la producción
4. Período de mantenimiento

La Etapa 1 consistió en reunir una gran cantidad de información sobre el proceso, equipos y negocio la cual estaba distribuida en varios sectores de la empresa y en el conocimiento experto de diferentes personas. Esta etapa se extendió en cierta medida, durante todo el proyecto debido a la gran cantidad de detalles involucrados en prácticamente todos los sectores del proceso/negocio.

En la Etapa 2 se desarrolló un modelo de simulación/optimización del proceso operativo, que consiste en balances de masa y energía detallados en cada nodo del diagrama de flujo de la Fig. 2. En esta etapa se requirió conocer en detalle la planta para modelar cada equipo, con el objetivo de monitorear los principales componentes de cada corriente a lo largo del proceso y estimar, con suficiente precisión, las variables importantes de cada una de las operaciones. Para varios sectores/equipos especialmente complicados (*decanters*, evaporadores, filtros), se desarrollaron modelos detallados utilizando primeros principios y se ajustaron luego con información de planta. Dichos modelos se utilizaron para obtener correlaciones que fueron luego integradas al modelo de simulación/optimización. Una actividad particularmente desafiante en el desarrollo de este módulo fue la de conciliar el modo de operación continua de la planta con las operaciones por lotes que tienen lugar en este proceso. Además de un seguimiento

completo de caudales, composiciones y temperaturas a lo largo de todo el proceso, este modelo permite el cálculo detallado de muchos índices de producción (KPI) de gran interés para los gerentes de planta. Se proporcionan más detalles en la siguiente sección.

En la Etapa 3 se desarrolló un módulo de planeamiento de la producción. Este módulo permite programar cada pedido de jugo a lo largo del horizonte de planeamiento de modo que se produzca y empaque a tiempo para que esté disponible para su envío en la fecha pactada. Este modelo requirió una comprensión completa del proceso de producción y de la logística involucrada.

La Etapa 4 consistió en el uso intensivo (diario) del sistema para detectar errores en los modelos e interfaces, e identificar posibilidades de mejora de las herramientas desarrolladas.

Una decisión estratégica importante, tomada al comienzo del proyecto, fue la selección de la plataforma de desarrollo. Siguiendo las recomendaciones del grupo de investigación, la compañía adoptó la plataforma de optimización GAMS con interfaces en Excel para la entrada de datos, la operación del modelo y la visualización de resultados. Este esquema resultó práctico ya que el personal de la compañía en todos los niveles está familiarizado con el software Excel y mucha información del proceso ya está en formato de hoja de cálculo, lo que permite su uso directo. Además, los modelos implementados en GAMS se pueden ejecutar, de manera transparente para el usuario, desde Excel incluso automáticamente.

Dado que la empresa/planta está ubicada en la ciudad de Villa Regina (provincia de Río Negro) y nuestro grupo de investigación está establecido en la ciudad de Bahía Blanca (provincia de Buenos Aires), a 450 km de distancia, se realizaron varias visitas de los miembros del grupo de investigación a la planta así como también visitas de los ingenieros de planta a Bahía Blanca a lo largo de la duración del proyecto para discutir los diferentes aspectos del proceso de producción y del negocio del jugo concentrado. Estas reuniones se complementaron con videoconferencias periódicas y numerosos correos electrónicos por mes.

Además, más de diez estudiantes universitarios de las carreras de Ingeniería Química e Ingeniería de Alimentos de la UNS se involucraron en el proyecto como PPS (Prácticas profesionales supervisadas) y/o pasantes. El resultado fue una experiencia enriquecedora para los estudiantes que se involucraron en un entorno industrial a través de un proyecto de modelamiento y también muchos de los resultados y conclusiones alcanzados por los alumnos contribuyeron al desarrollo de las herramientas. Esta interacción se convirtió en un resultado inesperado y positivo del proyecto. Desde el aspecto formal el proyecto se desarrolló en el marco de un convenio Conicet - Jugos S.A., y se registró como Proyecto de Desarrollo Tecnológico y Social (PDTS).

5 Sistema de Soporte a las Decisiones Basado en Modelos

Como se mencionó anteriormente, el SSD basado en modelos ideado para la planta de jugo concentrado de Jugos S.A. posee dos componentes principales: un modelo de simulación/optimización (SIMOPT) y un modelo de planeamiento de la producción

(PLANNER). El flujo de información entre ambos se muestra en la Fig. 3. El módulo SIMOPT realiza, básicamente, una optimización del proceso proporcionando información muy detallada del punto óptimo de operación de la planta junto a la estructura de costos desagregada, la cual es uno de los principales intereses para los gerentes de planta. Este módulo puede emplearse también para efectuar simulaciones específicas. El módulo PLANNER, que consta de tres modelos interactivos, realiza el programa de los lotes de los diferentes tipos de jugos que se elaborarán en el futuro cercano, considerando, esencialmente, compromisos (órdenes de compra), disponibilidad de fruta y pronósticos de ingresos de fruta.

Desde un punto de vista operativo, el sistema está diseñado para ejecutarse de forma modular o integrada cada vez que ingresa nueva información al sistema o se desea investigar un nuevo escenario. En particular, se supone que el planeamiento de la producción se ejecute diariamente, frecuencia típica de actualización del pronóstico de fruta entrante y la colocación de nuevos pedidos.

Cabe señalar que los modelos mencionados son determinísticos, es decir, todos los parámetros del modelo son fijos y conocidos. Tales datos se recopilan de varias bases de datos utilizadas habitualmente por los diferentes departamentos de la empresa y constituye la información más confiable disponible para la toma de decisiones en un entorno tan incierto. Se ha hecho un esfuerzo para que los modelos sean lo más sencillos posible para permitir realizar optimizaciones rápidas a medida que se recibe información actualizada, como una forma práctica e intuitiva de lidiar con la incertidumbre inherente a este complejo sistema.

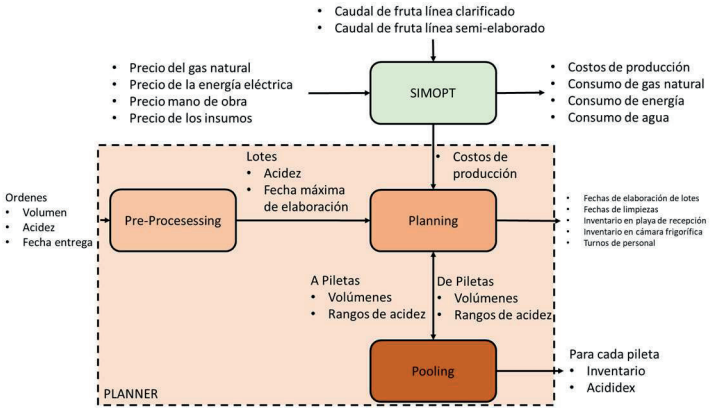


Fig. 3. Módulos basados en modelos y sus interacciones.

5.1 Módulo SIMOPT

El módulo SIMOPT consta de balances de masa y energía detallados en cada nodo del diagrama de flujo de la Fig. 2. Las corrientes del proceso se describen por tres componentes principales: sólidos solubles, sólidos insolubles y agua. La acidez no se controla en este módulo ya que es un parámetro ajustado en los procesos de mezcla que tienen lugar en la jerarquía de planeamiento de la producción. Dado un cierto flujo de fruta

que alimenta cada una de las líneas (clarificado y semielaborado), se resuelve un modelo orientado a optimizar el beneficio instantáneo del proceso, definido como el ingreso debido al jugo producido menos el costo total de la operación. Este último incluye el costo del uso de gas natural y electricidad y el costo por las operaciones de limpieza, envasado, transporte y almacenamiento. Como resultado, el caudal, la composición y la temperatura de cada corriente se reportan junto a los parámetros operativos más relevantes de cada equipo. Asimismo, se pueden elegir funciones objetivo adicionales, para realizar estudios específicos, como maximizar la producción, por ejemplo.

Dado que los balances de masa en los nodos de mezcla introducen bilinealidades y las ecuaciones de eficiencia de la mayoría de los equipos son regresiones no lineales de las variables de entrada, el modelo es no lineal. Además, también se incluyen varias variables binarias para modelar si un equipo en particular está funcionando o no. En particular, los turbos, *decanters*, plantas de ósmosis, evaporadores y calderas se encienden y apagan mediante el uso de variables binarias. Por lo tanto, el modelo es de programación no lineal mixto-entera (MINLP) y se resuelve con el *solver* DICOPT de la plataforma GAMS. Algunos datos básicos de los modelos se presentan en la Tabla 2. El panel de control SIMOPT se muestra en la Fig. 4.

Tabla 2. Estadísticas del Modelo.

	SIMOPT	**PLANNER**		
	Optimización	***Preprocessing***	***Planning***	***Pooling***
Tipo de Modelo	MINLP	MILP	MILP	MINLP
Ecuaciones	2 200	15 000	765 000	74 000
Variables Continuas	1 900	25 000	1 555 000	22 000
Variables Binarias	70	1 700	10 900	17 000
Tiempo de CPU (min)	0.2	7	7	0.3

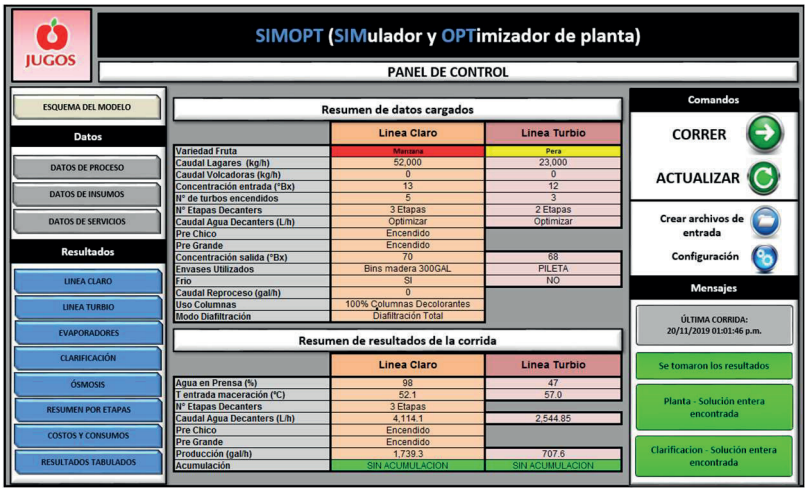


Fig. 4. Panel de control del módulo SIMOPT.

5.2 Módulo PLANNER

Para manejar de forma práctica la gran cantidad de decisiones involucradas, el planeamiento de la producción se organiza mediante una herramienta PLANNER, que coordina la interacción de tres submódulos (*Preprocessing*, *Planning*, y *Pooling*) que realizan actividades diferentes y complementarias. El panel de control correspondiente se muestra en la Fig. 5.

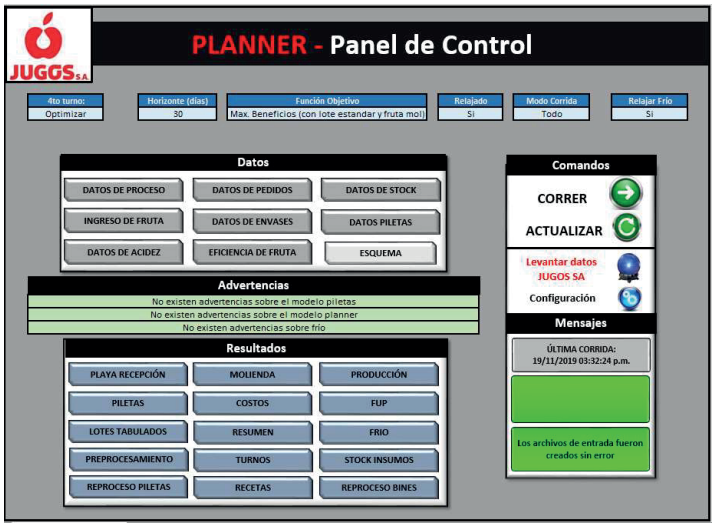


Fig. 5. Panel de control del módulo PLANNER.

El modelo de planeamiento propuesto adopta un enfoque multiperíodo que abarca tres meses con resolución diaria. Para un conjunto establecido de pedidos de jugo de diferentes tipos (manzana, pera, orgánicos, etc.) y rangos de acidez que se deben entregar a lo largo del horizonte de planeamiento y una dada estimación de la disponibilidad de fruta fresca en el futuro, el módulo calcula los días específicos en que deben fabricarse los lotes de cada tipo de jugo. El objetivo es optimizar el beneficio total del negocio, definido como el ingreso por el jugo producido menos todos los costos involucrados integrados a lo largo del horizonte de planeamiento.

Además de las decisiones de producir un lote de jugo en particular en un día específico, se deben tomar muchas otras decisiones binarias cada día del horizonte. Dichas decisiones involucran, por ejemplo, la manera en que se distribuye un determinado pedido de jugo en los lotes cuya producción se programará, el momento en que se apagan las diferentes líneas para su limpieza, la cantidad de jugo retirado de las cámaras de frío los días de envío, la cantidad de jugo semielaborado de cada tipo de fruta enviado y retirado de las piletas, etc. El número de variables binarias es, por lo tanto, enorme. Además, las piletas de jugo semielaborado introducen una complejidad considerable ya que la mezcla de jugos de diferente acidez tiene lugar en estas piletas, introduciendo no linealidades en el modelo. Por estas razones, un modelo único para el planeamiento completo de la producción es un problema MINLP enorme cuya resolución es

incompatible con la toma de decisiones diaria. Para desarrollar herramientas prácticas, el módulo de planeamiento se estructuró en tres submódulos interactivos, cada uno orientado a un conjunto específico de decisiones.

Preprocessing. Este submódulo recibe los pedidos de jugo realizados por los clientes. Estas órdenes definen un cierto volumen de jugo concentrado clarificado de un tipo particular (manzana, pera, orgánico, tradicional) dentro de un rango de acidez específico (ej. 1.0 - 1.4 g / L), en un empaque determinado (contenedores, tambores, etc.) que debe ser entregado en una fecha particular o distribuido a lo largo de ciertas fechas específicas. Cada día la planta puede producir un lote con un volumen específico (en galones) de jugo clarificado de cualquier tipo. Dado que algunos pedidos pueden ser más pequeños que un lote y otros requerir varios lotes para completarlos, surge un problema sobre cómo distribuir los pedidos en los lotes para que se elaboren a tiempo, verificando la acidez y los requerimientos de empaque de cada uno.

El submódulo de *Preprocessing* realiza esta tarea resolviendo un problema específico para cada tipo de jugo: (i) jugo de manzana convencional, (ii) jugo de pera convencional, (iii) jugo de manzana orgánico, (iv) jugo de pera orgánico. Para cada tipo de producto, se resuelve un modelo MILP que asigna las órdenes a los lotes a producir. De esta manera, un lote puede tener jugo que pertenece a más de un pedido que tienen el mismo rango de acidez y tipo de empaque. En todos los casos, el objetivo principal es minimizar el número de lotes para cumplir con todas las órdenes. La fecha de producción de cada lote tiene que verificar, por supuesto, la fecha de entrega de la orden asignada más cercana. El problema de asignar las órdenes a los lotes se resuelve con el *solver* CPLEX. El detalle de las órdenes se obtiene del sistema de la empresa y se alimenta automáticamente al submódulo *Preprocessing*. Los resultados de este módulo son los lotes que se deberán producir antes de ciertas fechas máximas, los que se cargan, de manera automática, al submódulo *Planning* donde se obtiene la programación final de los mismos.

Planning. El submódulo *Planning* es el componente principal de la herramienta de planeamiento de la producción (PLANNER). Recibe desde el submódulo *Preprocessing* el número de lotes para un determinado tipo de fruta y acidez que se deberán producirán en el futuro con las fechas máximas correspondientes. También tiene acceso a un pronóstico de ingreso para los distintos tipos de fruta. Desde el módulo SIMOPT, *Planning* recibe los valores actualizados de los costos de producción y almacenamiento. El resultado principal del submódulo es la programación de lotes a lo largo del horizonte de planeamiento. Algunos lotes corresponden a órdenes de compra específicas según lo requerido por el submódulo *Preprocessing*. No obstante, cuando la producción de jugo semielaborado no alcanza a evitar la acumulación excesiva de fruta en el área de recepción, *Planning* programa, automáticamente, la producción de lotes de jugo de calidad estándar para almacenar en frío.

El programa obtenido proporciona, además, las fechas en que las líneas deben apagarse para su limpieza antes de cambiar entre especies de frutas. Asimismo, considera las fechas específicas para la limpieza programada de las líneas de acuerdo con las normas correspondientes. Después de la temporada de cosecha, el modelo también

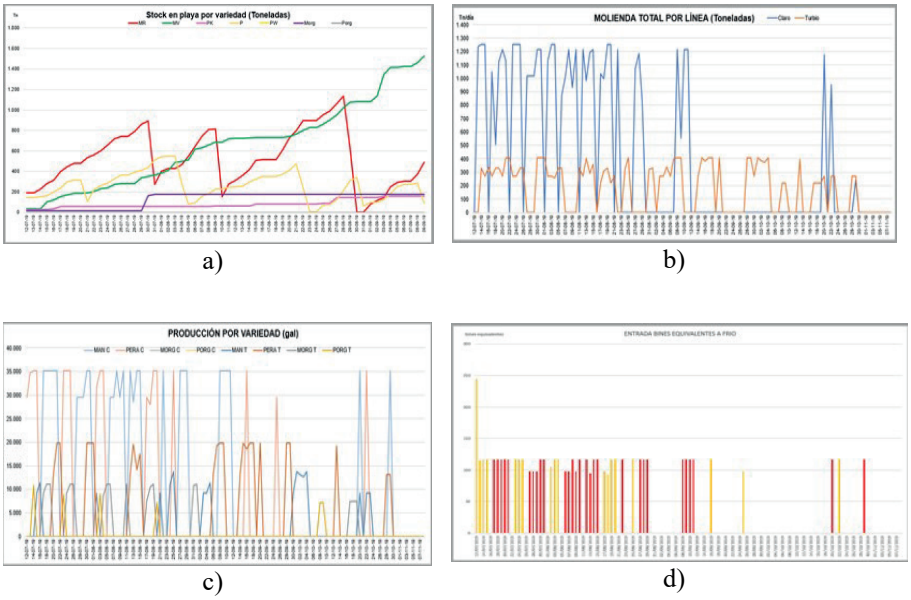
predice los períodos en los que la planta debe permanecer inactiva esperando que se acumule fruta en cantidades significativas para reiniciar la producción. Otros resultados incluyen inventarios del área de recepción y de la cámara de frío.

Otro conjunto de decisiones importantes se refiere a la cantidad de jugo semielaborado que se producirá cada día y será almacenado en piletas, así como la cantidad de jugo semielaborado que reingresa al proceso desde las piletas para elaborar los lotes. Estas decisiones demandan un número significativo de variables binarias para su modelado. Además, la mezcla de jugo en las piletas introduce bilinealidades dado que tanto los volúmenes como la acidez son variables de decisión. Por lo tanto, la operación de las piletas tiene asociado un subconjunto de ecuaciones no lineales mixto-enteras, lo que complica aún más el ya complejo modelo de programación de la producción. Para evitar la complejidad de este proceso, la acidez se manejó de manera simplificada a nivel *Planning* y los balances rigurosos de las piletas se asignaron en un submódulo complementario denominado *Pooling*.

Aunque el modelo sigue siendo lineal, la gran cantidad de variables binarias impide su resolución en tiempos de cálculo razonables para todo el horizonte de planeamiento adoptado de 90 días. Para generar un programa en tiempos razonables, digamos unos 30 min de CPU, se optó por resolver secuencialmente una serie de subproblemas relativamente pequeños y fáciles de 10 días de extensión en un esquema de horizonte móvil. Por lo tanto, se resuelven nueve subproblemas de diez días para cubrir el horizonte de planeamiento de 3 meses. La solución obtenida para cada modelo se fija antes de abordar la solución del siguiente problema. La función objetivo principal a optimizar es el beneficio general de la operación definida como el ingreso producido por la venta de los lotes menos los costos de ejecutar el proceso. Para estudios específicos se pueden elegir funciones objetivo adicionales, tales como maximizar la producción de jugo concentrado (clarificado, semielaborado o ambos). En la Tabla 2 se informa el tamaño del modelo de *Planning* para un período de diez días, que se resuelve con el *solver* CPLEX. En la Fig. 6, se presentan los perfiles de algunas variables características para ilustrar algunos de los resultados del submódulo *Planning*. La Fig. 6 a) muestra los perfiles típicos de los inventarios de las diferentes variedades de fruta en el área de recepción. La Fig. 6 b) muestra las cantidades de fruta procesadas por las líneas de jugo clarificado y semielaborado (azul y naranja, respectivamente). La capacidad de la línea de jugo clarificado es aproximadamente tres veces mayor que la de la línea de jugo semielaborado. La Fig. 6 c) presenta las cantidades de jugo de diferentes tipos producidas cada día. Finalmente, en la Fig. 6 d) se muestran, en formato de barras, los lotes de diferentes productos que ingresan a la cámara frigorífica.

Existen muchas fuentes de infactibilidad en el modelo de *Planning*. Por ejemplo, si no hay suficiente fruta en el sitio de recepción y jugo semielaborado en las piletas de almacenamiento, la producción de algunos lotes puede no ser factible en los próximos días. En estos casos, cuando se detecta la infactibilidad, se activan secuencialmente varias relajaciones que se manifiestan lo más lejos posible en el horizonte de planificación, de modo de generar un programa factible. Por ejemplo, si el nivel de acidez de algún lote no se puede lograr en el futuro, se relaja en cierta medida utilizando un valor menos restrictivo. De esta manera, generalmente se logra una solución factible y se muestra una señal de advertencia en la interfaz de resultados, para que pueda ser

analizada luego por los ingenieros de proceso. Las soluciones relajadas no tienen un impacto práctico en las decisiones que se tomarán en los días inmediatos y advierten, por lo general, sobre la escasez de ciertos tipos de fruta que puede ocurrir en el futuro.



a) b) c) d)

Fig. 6. Resultados del módulo *Planning*.

Pooling. Como se describió previamente, el manejo del jugo semielaborado se aborda de manera muy simple en la etapa de *Planning* para evitar no linealidades y variables binarias que complicarían excesivamente una solución práctica del modelo de planeamiento de la producción. Para seguir en detalle el tipo, nivel de inventario y acidez del jugo en cada pileta, se representó el funcionamiento del sistema de piletas de almacenamiento con otro modelo denominado *Pooling*. Para cada pileta, los balances de inventario (lineales) y los balances de acidez y °Brix (no lineales) se realizan cada día del horizonte de planeamiento. Además, se utilizan variables binarias para controlar el tipo de jugo que se almacena en cada pileta cada día.

Una vez que se resuelve el *Planning* para el período de 90 días, se establecen las cantidades de jugo semielaborado que se envían cada día a las piletas de almacenamiento, así como las cantidades de jugo semielaborado que se requieren de las piletas cada día para producir lotes específicos de jugo clarificado. Por lo tanto, *Pooling* recibe como parámetros las entradas específicas de jugo (cantidad y acidez) al sistema de piletas y también las salidas (cantidad y acidez) que se retirarán del sistema cada día del horizonte de planeamiento. En esta etapa, se resuelve un problema de optimización para distribuir el jugo entrante a la pileta de almacenamiento más apropiada y para satisfacer lo más ajustadamente posible, en cantidad y acidez, el jugo para reprocesamiento.

Para evitar infactibilidades en caso de que la cantidad exacta de jugo semielaborado con el nivel de acidez requerido no se puede entregar en algunos períodos futuros, la función objetivo del *Pooling* es minimizar las desviaciones con respecto a los valores requeridos. Si estas desviaciones son significativas, se generan advertencias en la interfaz de usuario. *Pooling* es un modelo MINLP de 90 días resuelto con el *solver* DICOPT. Para aumentar la robustez proporcionando un buen punto de partida para el sistema no lineal se resuelve, en primer lugar, un problema lineal aproximado utilizando valores de acidez promedio para todas las corrientes. La solución de este problema se utiliza como punto inicial del modelo no-lineal original de mezclado. Las estadísticas básicas de este modelo se presentan en la Tabla 2.

6 Conclusiones

El desarrollo de las herramientas descritas para asistir en el proceso de toma de decisiones de la compañía Jugos S.A. presentó varios desafíos para el equipo de desarrollo integrado por miembros de nuestro grupo de investigación e ingenieros de la compañía. El primero fue alcanzar un consenso en cuanto al número y tipo de modelos a desarrollar y al nivel de detalle a incluir en cada uno. Aunque prácticamente cada parte importante del proceso fue modelada y ajustada con datos de planta, en los módulos centrales descritos en este trabajo (SIMOPT y PLANNER), algunos de los subprocesos finalmente fueron representados por regresiones sencillas generadas con datos obtenidos de esos modelos más sofisticados. De esta forma se logró conciliar un nivel de detalle adecuado con tiempos de resolución prácticos.

Otro desafío al que se enfrentó nuestro equipo fue reunir la cantidad de información necesaria sobre las unidades, el proceso y el negocio. Cabe destacar que el negocio cambia año tras año debido al contexto e incertidumbre tanto local como internacional. Además, el proceso es flexible y se adapta a los nuevos requisitos de producción. Abordamos estos desafíos discutiendo cada tema específico en profundidad, proponiendo una determinada solución de modelado, probándola, comparando los resultados con las estimaciones esperadas e introduciendo mejoras hasta llegar a un acuerdo sobre la validez del enfoque adoptado. Por ejemplo, la definición de la función objetivo más conveniente para que cada módulo se asemeje a la práctica operativa real, fue una actividad laboriosa a lo largo de toda la duración del proyecto.

A nivel de desarrollo, los cuatro modelos descritos en este documento plantearon importantes desafíos de modelamiento. La estrategia de descomposición ideada para producir programas razonables en tiempos prácticos de ejecución es compatible con la gran incertidumbre que enfrenta el sistema en el horizonte de planeamiento adoptado.

Además de una herramienta para generar automáticamente programas detallados y permitir estudios de escenarios, el sistema también proporciona pautas para operar el proceso a largo plazo. La información reportada por los modelos constituye hoy en día una forma sistemática de visualizar todo el proceso/negocio entre el personal de diferentes departamentos y proporciona un marco común para la discusión del planeamiento estratégico dentro de la empresa. Esta experiencia ha sido reportada en [10].

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Optimización de la Trazabilidad en la Cadena de Suministro de la Carne

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Resumen. En las últimas décadas se han tomado medidas para dar solución a los diferentes problemas de salud pública causados por alimentos. Entre ellas, es de destacada importancia la trazabilidad, cuyo fin es, rastrear los productos de forma eficiente. El objetivo de este trabajo es minimizar la dispersión total de los lotes en la cadena de suministros de productos cárnicos para optimizar su trazabilidad. Para ello se desarrolla un modelo de programación mixta entera lineal (MILP), cuyas variables de decisión se emplean para determinar la existencia y el número de lotes en cada nivel, las cantidades involucradas y los actores que participan. Los resultados muestran que se puede generar una cantidad de lotes óptima y disminuir la dispersión de los mismos, minimizando así, los costos de retiro de los productos ante una crisis de seguridad alimentaria. Además, la formulación permite el rastreo de los lotes de producto en cada punto de la cadena de suministro identificando los lotes de animal y materias primas utilizados en su elaboración.

Palabras Claves: Cadena de Suministro de la Carne, Dispersión por Lotes, Trazabilidad, MILP, Optimización.

1 Introducción

Debido a los diferentes problemas de salud pública causados por los alimentos en las últimas décadas, los consumidores exigen cada vez más información sobre su calidad e inocuidad. Esta creciente preocupación por la seguridad alimentaria ha generado una mayor presión no sólo sobre los productores y distribuidores de alimentos sino también sobre las autoridades competentes para establecer sistemas y reglamentaciones que permitan identificar, controlar y rastrear un alimento desde su origen hasta el final de su comercialización [1]. Es en este contexto que los sistemas de trazabilidad han tomado notoriedad constituyendo una herramienta clave para gestionar el riesgo y calidad de los productos en diferentes Cadenas de Suministro (CS) agroalimentarias, en general, y en la CS de la Carne (CSC), en particular.

Aunque existen diversas acepciones de trazabilidad, según el *Codex Alimentarius* [2], se la define como “la capacidad para seguir el movimiento de un alimento a través de etapa(s) específica(s) de la producción, transformación y distribución”. Así,

establecer un sistema de trazabilidad es un método efectivo para garantizar la seguridad alimentaria acreditando que los alimentos son sanos y fiables y que, ante cualquier problema, se cuenta con la información para limitar su riesgo permitiendo, si es necesario, retirar partidas del mercado. Sin embargo, este sistema no disminuye la cantidad de productos retirados en aquellos casos en que la producción se realice por mezcla de lotes como sucede, por ejemplo, en la elaboración de productos cárnicos.

En la industria de los alimentos, lotes de materia prima provenientes de diversos proveedores, con diferentes calidades y precios, a menudo se mezclan para obtener lotes de productos terminados. Esto se conoce como el problema de dispersión por lotes, en el cual se tienen procesos de desensamblado/desarmado y ensamblado/armado durante la producción [3]. La mezcla de lotes de materias primas en distintos lotes de producto incrementa no sólo la complejidad en su trazabilidad hacia atrás o *tracing* sino también la probabilidad de contaminación del alimento que podría causar el retiro de productos.

A nivel planta, Dupuy y col. [4] es uno de los trabajos pioneros en abordar a el problema de dispersión por lotes desde un enfoque de modelado matemático. Estos autores desarrollaron un modelo de programación mixta entera lineal (MILP) para optimizar la trazabilidad minimizando la dispersión durante la elaboración de salchichas, controlando la mezcla de lotes de producción para limitar el tamaño y, en consecuencia, el costo y el impacto mediático del retiro de los lotes de producto en caso de problemas. Luego, Tamayo y col. [5] emplearon algoritmos genéticos para resolver el mismo problema propuesto en [4]. Hu y col. [6] propusieron un modelo matemático basado en programación dinámica para mejorar el sistema de trazabilidad en una fábrica China de dumplings al minimizar los lotes de producto retirados del mercado ante posibles crisis de seguridad alimentaria. Dabbene y col. [7] plantearon una nueva formulación MILP para optimizar la trazabilidad en el que se utiliza un grafo interconectado para representar al proceso de producción. Estos autores adoptan directamente el costo de retirada del mercado para el peor caso como criterio desempeño del modelo y para demostrar su efectividad lo aplican al mismo ejemplo presentado en [4].

Respecto a la trazabilidad en la CSC, Vélez Cervantes [8] desarrolló un modelo lineal (LP) para planificar la CS pesquera de Esmeraldas (Ecuador) donde implementa un "sistema de gestión de trazabilidad" considerando la calidad de los mariscos alrededor de cada nodo de la CS. Por otra parte, Mohammed y col. [9] desarrollaron un modelo MILP difuso multiobjetivo para el diseño y planificación de la distribución de productos en la CSC que incorpora la trazabilidad mediante el cálculo de los costos por el uso del sistema de identificación por radiofrecuencia (RFID).

De acuerdo a nuestro conocimiento, no se ha implementado aún la integración de la trazabilidad y la dispersión por lotes en las CSCs. Por ello, en este trabajo se presenta un modelo MILP para la optimización de la trazabilidad mediante la reducción de la dispersión de los lotes en toda la CSC. El problema permite además determinar los actores involucrados en la producción de los productos cárnicos y calcular el tamaño y número de lotes de materias primas y productos generados en las plantas y aquellos producidos en los frigoríficos, identificando los que serán utilizados en la elaboración de cada producto final logrando así su rastreo a lo largo de la cadena.

2 Definición del Problema

El problema bajo estudio se basa en optimizar el sistema de trazabilidad de la CSC compuesta por tres eslabones, como se muestra en la Fig. 1. Cada frigorífico $f \in \{1,\ldots, F\}$ faena una o más especies animales $a \in \{1,\ldots, A_f\}$, generándose los lotes $h \in \{1,\ldots, H_{af}\}$ para cada una de ellas. Los animales son vendidos en forma de media res a los establecimientos elaboradores $e \in \{1,\ldots, E\}$ donde se los desposta en $m \in \{1,\ldots, M_e\}$ materias primas, generándose $i \in \{1,\ldots, I_{me}\}$ lotes de las mismas. En una etapa posterior de la planta, la materia prima se corta para obtener los componentes $c \in \{1,\ldots, C_e\}$ que luego, de acuerdo a una receta conocida, se mezclan en las proporciones adecuadas para obtener los lotes $k \in \{1,\ldots, K_{pe}\}$ de cada producto $p \in \{1,\ldots, P_e\}$ elaborado por el establecimiento *e*. Finalmente, los productos *p* serán distribuidos a cada minorista $r \in \{1,\ldots, R\}$ de manera de satisfacer su demanda D_{pr} en un horizonte de tiempo *HT*.

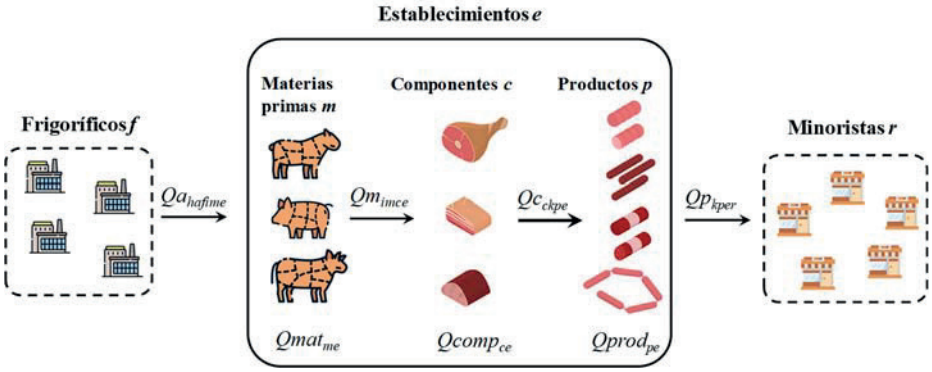

Fig. 1. Estructura de la CSC en estudio.

En este problema se tiene como datos en cada establecimiento *e*, la especificación de los diversos cortes *m* que se realizan a las medias reses de cada animal *a* procesado, la definición del trozado de la materia prima *m* para obtener los componentes *c* y las recetas de producción que detallan los componentes *c* utilizados en la elaboración de los productos finales *p*. Los siguientes parámetros representan esta información:

- Pa_{am}: es la proporción de materia prima *m* que se obtiene del animal *a*.
- Pm_{mc}: es la proporción de componente *c* que se obtiene de la materia prima *m*.
- Pc_{cp}: es la proporción de componente *c* que formará parte del producto *p*.

La cantidad de producto *p* demandada por cada minorista *r*, D_{pr}, es un parámetro del modelo y se conocen, además, los tamaños máximos y mínimos posibles para los lotes de animal *a* en cada frigorífico *f* ($bt_{af}^{\max}$, $bt_{af}^{\min}$) y, para cada lote de materia prima *m* ($b_{me}^{\max}$, $b_{me}^{\min}$) y producto *p* ($bs_{pe}^{\max}$, $bs_{pe}^{\min}$) dentro de los establecimientos *e*. Dichas cotas se basan en la capacidad máxima y mínima de procesamiento o almacenamiento del actor o etapa correspondiente. Es importante destacar que se propone el número máximo de lotes de animal, materia prima y producto (es decir, el número máximo de

elementos de los conjuntos H_{af}, I_{me} y K_{pe}), respectivamente. Este número se determina en función del mínimo tamaño posible del lote correspondiente y de la demanda.

La función objetivo del problema consiste en minimizar la dispersión de los lotes durante la elaboración de productos cárnicos, es decir, desde la compra del animal al frigorífico hasta obtener el producto, considerando cada paso del proceso de elaboración.

En resumen, el problema consiste en determinar simultáneamente lo siguiente:

a) el frigorífico proveedor, la cantidad de animal requerida y el tamaño de sus lotes, identificando el lote que se envía a cada establecimiento,
b) el tamaño y la cantidad de lotes de materia prima generados en cada establecimiento y cuál de ellos se usa en la elaboración de cada producto,
c) el tamaño y número de lotes de producto en cada establecimiento,
d) el establecimiento que abastece a cada minorista, identificando el producto y el lote que recibe cada uno.

Por lo tanto, este modelo permite identificar el lote de animal (de un dado frigorífico) que genera el lote de producto que recibe el minorista, representando así la trazabilidad del producto.

3 Formulación del Modelo

En esta sección se detalla la formulación del modelo MILP propuesto para minimizar la dispersión de los lotes en la CSC.

3.1 Restricciones de los frigoríficos

En primer lugar, para determinar los lotes generados en los frigoríficos se define la siguiente variable binaria:

$$x_{haf} = \begin{cases} 1 \text{ si el batch } h \text{ de animal } a \text{ se genera en el frigorífico } f \\ 0 \text{ en caso contrario} \end{cases}$$

$$BT_{haf} \leq bt_{af}^{\max} \cdot x_{haf} \qquad \forall h \in H_{af}, a \in A_f, f \tag{1}$$

$$BT_{haf} \geq bt_{af}^{\min} \cdot x_{haf} \qquad \forall h \in H_{af}, a \in A_f, f \tag{2}$$

Las Ecs. (1) y (2) establecen que el tamaño del lote h de animal a en el frigorífico f, BT_{haf}, se encuentre entre su cota superior e inferior ($bt_{af}^{\max}$, $bt_{af}^{\min}$), respectivamente. Además, estas restricciones aseguran que el tamaño del lote sea cero si el lote no se genera ($x_{haf} = 0$).

$$x_{h+1,af} \leq x_{haf} \qquad \forall\, 1 \leq h < H_{af}, a \in A_f, f \tag{3}$$

La Ec. (3) asegura que los lotes *h* en cada frigorífico *f* se generen en orden ascendente, es decir, el lote *h*+1 puede generarse sólo si el lote *h* ya fue generado.

$$Qan_{af} = \sum_{h \in H_{af}} BT_{haf} \qquad \forall a \in A_f, f \tag{4}$$

La Ec. (4) define la cantidad total de animal *a* procesada en el frigorífico *f*, Qan_{af}, como la suma de las bachadas *h* generadas en el mismo.

$$Pa_{am} \cdot BT_{haf} = \sum_{e} \sum_{i \in I_{me}} Qa_{hafime} \qquad \forall h \in H_{af}, a \in A_f, f, m \in MR_{ae} \tag{5}$$

La Ec. (5) expresa que cada lote *h* de medias reses del animal *a* que se envía a los establecimientos productores *e*, es despostado para obtener los cortes de materia prima *m*, respetando la proporción Pa_{am}. La variable continua Qa_{hafime} representa la cantidad de animal *a* en el lote *h* enviada desde el frigorífico *f* al establecimiento *e* contenida en el lote *i* de materia prima *m* y el subconjunto MR_{ae} contiene aquellas materias primas *m* que se obtienen del animal *a* en la planta *e*.

$$\sum_{e} \sum_{m \in MR_{ae}} \sum_{i \in I_{me}} Qa_{hafime} \leq Qa_{af}^{\max} \cdot x_{haf} \qquad \forall h \in H_{af}, a \in A_f, f \tag{6}$$

Si el batch *h* de animal *a* en el frigorífico *f* existe (es decir, $x_{haf} = 1$), la Ec. (6) asegura que la cantidad Qa_{hafime} sea menor que la cantidad máxima de animal que se puede procesar en el frigorífico *f*, $Qa_{af}^{\max}$.

$$BT_{h+1,af} \leq BT_{haf} \qquad \forall\, 1 \leq h < H_{af}, a \in A_f, f \tag{7}$$

Para evitar soluciones alternativas, la Ec. (7) asegura que los tamaños de bachada también sigan un orden creciente.

3.2 Restricciones de los establecimientos

Restricciones de las materias primas
Se define la variable binaria:

$$w_{ime} = \begin{cases} 1 \text{ si el batch } i \text{ de materia prima } m \text{ se genera en el establecimiento } e \\ 0 \text{ en caso contrario} \end{cases}$$

$$\sum_{e} \sum_{m \in MR_{ae}} w_{ime} \leq \sum_{f} \sum_{h \in H_{af}} x_{haf} \quad \forall a \in A_f, i \in I_{me} \tag{8}$$

La restricción (8) asegura que si no se generan bachadas *h* del animal *a* entonces no se podrán generar lotes *i* de las materias primas *m* que provienen de ese animal en ningún establecimiento *e*.

$$B_{ime} \le b_{me}^{\max} \cdot w_{ime} \qquad \forall i \in I_{me}, m \in M_e, e \tag{9}$$

$$B_{ime} \ge b_{me}^{\min} \cdot w_{ime} \qquad \forall i \in I_{me}, m \in M_e, e \tag{10}$$

En caso de que se genere el batch *i* de materia prima *m* en el establecimiento *e*, es decir w_{ime} = 1, su tamaño B_{ime} estará delimitado por sus cotas superior $b_{me}^{\max}$ e inferior $b_{me}^{\min}$ como establecen las Ecs. (9) y (10), respectivamente.

$$w_{i+1,me} \le w_{ime} \qquad \forall 1 \le i < I_{me}, m \in M_e, e \tag{11}$$

Mediante la Ec. (11) se garantiza que la generación de lotes *i* se realice en orden creciente.

$$B_{ime} = \sum_{f} \sum_{a \in A_f} \sum_{h \in H_{af}} Qa_{hafime} \qquad \forall i \in I_{me}, m \in M_e, e \tag{12}$$

Debido a que un lote *i* de materia prima *m* en cada establecimiento *e* se puede obtener a partir de diferentes lotes *h* del animal *a* recibidos de distintos frigoríficos *f*, la Ec. (12) establece que su tamaño, B_{ime}, es igual a la sumatoria de las cantidades que llegan desde todos ellos para formarlo.

$$\sum_{f} \sum_{a \in A_f} \sum_{h \in H_{af}} Qa_{hafime} \le Qa_{af}^{\max} \cdot w_{ime} \qquad \forall i \in I_{me}, m \in M_e, e \tag{13}$$

Si el batch *i* de materia prima *m* en el establecimiento *e* existe (w_{ime}=1), entonces, según lo establece la Ec. (13), la cantidad de animal *a* en el lote *h* enviada por el frigorífico *f* al establecimiento *e* contenida en el lote *i* de materia prima *m* Qa_{hafime}, no debe superar su cota superior, $Qa_{af}^{\max}$.

$$Qmat_{me} = \sum_{i \in I_{me}} B_{ime} \qquad \forall m \in M_e, e \tag{14}$$

La cantidad total de materia prima *m* disponible en cada establecimiento *e*, $Qmat_{me}$, queda definida por la suma de los lotes *i* generados para la misma (Ec. 14).

$$Pm_{mc} \cdot B_{ime} \ge Qm_{imce} \qquad \forall i \in I_{me}, m \in M_e, c \in CS_{me}, e \tag{15}$$

La Ec. (15) representa el desarmado de la materia prima *m* para obtener los componentes o trozos de carne *c*, respetando la proporción conocida Pm_{mc}. Aquí, la variable continua Qm_{imce} es la cantidad del componente *c* que proviene del batch *i* de la materia prima *m* y el subconjunto CS_{me} incluye a los componentes *c* que provienen de la materia prima *m* en el establecimiento *e*.

$$Qmat_{me} \geq \sum_{c \in CS_{me}} \sum_{i \in I_{me}} Qm_{imce} \qquad \forall m \in M_e, e \tag{16}$$

La Ec. (16) establece que la suma de las cantidades de todos los componentes *c* obtenidos a partir de los lotes *i* no podrá ser mayor que la cantidad total de materia prima *m* a partir de la cual se originan.

$$Qm_{imce} \leq Qm_{me}^{\max} \cdot w_{ime} \qquad \forall i \in I_{me}, m \in M_e, c \in CS_{me}, e \tag{17}$$

La Ec. (17) impide que la cantidad del componente *c* proveniente del batch *i* de la materia prima *m* en el establecimiento *e,* supere la cantidad máxima de materia prima que se puede procesar en el establecimiento, $Qm_{me}^{\max}$.

$$B_{i+1,me} \leq B_{ime} \qquad \forall 1 \leq i < I_{me}, m \in M_e, e \tag{18}$$

La Ec. (18) garantiza que el de tamaño de los lotes de materia prima se generen en orden ascendente evitando así soluciones alternativas.

Restricciones de los componentes

$$Qcomp_{ce} = \sum_{m \in MS_{ce}} \sum_{i \in I_{me}} Qm_{imce} \quad \forall c \in C_e, e \tag{19}$$

La Ec. (19) establece que la cantidad de componente *c* producida en el establecimiento *e*, $Qcomp_{ce}$, proviene exclusivamente de la suma de los lotes *i* de las materias primas *m* que se procesaron en la planta. El subconjunto MS_{ce} contiene a las materias primas que pueden generar el componente *c*.

$$Qcomp_{ce} = \sum_{p \in PS_{ce}} \sum_{k \in K_{pe}} Qc_{ckpe} \qquad \forall c \in C_e, e \tag{20}$$

A su vez, la Ec. (20) define que $Qcomp_{ce}$ sea igual a la suma de las cantidades de componente *c* utilizadas en la elaboración de todos los lotes *k* de los productos *p*, Qc_{cpke}. Aquí, el subconjunto PS_{ce} incluye a los productos que se pueden elaborar con el componente *c* en la planta *e*.

Restricciones de los productos
Se define la variable binaria:

$$z_{kpe} = \begin{cases} 1 \text{ si el batch } k \text{ de producto } p \text{ se genera en el establecimiento } e \\ 0 \text{ en caso contrario} \end{cases}$$

$$BS_{kpe} \leq bs_{pe}^{\max} \cdot z_{kpe} \qquad \forall k \in K_{pe}, p \in P_e, e \tag{21}$$

$$BS_{kpe} \geq bs_{pe}^{\min} \cdot z_{kpe} \qquad \forall k \in K_{pe}, p \in P_e, e \tag{22}$$

La variable z_{kpe} se activa mediante las Ecs. (21) y (22) donde el tamaño del lote k de producto p en el establecimiento e, BS_{kpe}, puede tomar un valor distinto de cero sólo si $z_{kpe} = 1$. Los parámetros $bs_{pe}^{\max}$ y $bs_{pe}^{\min}$ son las cotas máximas y mínimas, respectivamente.

$$z_{k+1,pe} \leq z_{kpe} \qquad \forall 1 \leq k < K_{pe}, p \in P_e, e \tag{23}$$

Al igual que en las secciones previas, la Ec. (23) se incorpora con la finalidad de reducir el espacio de búsqueda garantizando que las bachadas k del producto p en el establecimiento e se generen en orden ascendente.

$$Qprod_{pe} = \sum_{k \in K_{pe}} BS_{kpe} \qquad \forall p \in P_e, e \tag{24}$$

La cantidad total de producto p elaborado en el establecimiento e, $Qprod_{pe}$, se define en la Ec. (24) igual a la suma de todos los lotes k del producto p elaborados en el mismo.

$$Pc_{cp} \cdot BS_{kpe} = Qc_{ckpe} \qquad \forall c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{25}$$

La cantidad de componente c que formará parte del lote k de producto p en un dado establecimiento e, Qc_{ckpe} se calcula en la Ec. (25) donde cada batch k de producto p elaborado debe respetar la proporción Pc_{cp} dada en la receta de producción. El subconjunto CR_{pe} incluye los componentes que se utilizan para elaborar el producto p en el establecimiento e.

$$Qc_{ckpe} \leq Qc_{ce}^{\max} \cdot z_{kpe} \qquad \forall c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{26}$$

La Ec. (26) impide que la cantidad de componente c usada para elaborar el batch k de producto p en el establecimiento e supere la cantidad máxima de componente que se puede procesar, $Qc_{ce}^{\max}$. Esta cota solo se aplica si existe el lote k de producto p en el establecimiento e.

$$Qprod_{pe} = \sum_{c \in CR_{pe}} \sum_{k \in K_{pe}} Qc_{ckpe} \qquad \forall p \in P_e, e \tag{27}$$

El balance de masa de la Ec. (27) establece que la cantidad de producto p será igual a la suma de los componentes c que lo conforman.

$$BS_{k+1,pe} \leq BS_{kpe} \qquad \forall 1 \leq k < K_{pe}, p \in P_e, e \tag{28}$$

Para mejorar el proceso de resolución del problema la Ec. (28) elimina soluciones equivalentes al obligar que el tamaño de bachada de un número de lote menor, sea mayor o igual que el tamaño del número de lote siguiente.

3.3 **Restricciones de los minoristas**

$$D_{pr} = \sum_{e} \sum_{k \in K_{pe}} Qp_{kper} \qquad \forall p \in P_e, r \tag{29}$$

Sea Qp_{kper} una variable no negativa que representa la cantidad de producto p perteneciente al lote k que se elabora en la planta e y se distribuye al minorista r. La Ec. (29) asegura que la satisfacción de la demanda del producto p en los distintos minoristas r, la cual será cubierta utilizando tantos lotes k del producto p como sean necesarios que podrán provenir de uno o más establecimientos e.

$$\sum_{r} Qp_{kper} \leq BS_{kpe} \qquad \forall k \in K_{pe}, p \in P_e, e \tag{30}$$

La Ec. (30) establece que la cantidad de producto p perteneciente al batch k producido en un dado establecimiento e que se envía a todos los minoritas de la CS deberá ser menor o igual que el tamaño de lote, BS_{kpe}.

$$\sum_{k \in K_{pe}} \sum_{r} Qp_{kper} \leq Qprod_{pe} \qquad \forall p \in P_e, e \tag{31}$$

A su vez, la cantidad total de producto p que se puede enviar a los minoristas, no puede superar a la cantidad de producto p disponible en el establecimiento e, $Qprod_{ep}$, como se evidencia en la Ec. (31).

3.4 **Restricciones de utilización de bachadas**

Con el fin de relacionar los lotes en la CS, se introducen las variables binarias:

v_{hafime} = { 1 si el batch h de animal a es usado en el batch i de materia prima m en el establecimiento e
0 en caso contrario

y_{imckpe} = { 1 si el batch i de materia prima m genera el componente c y este es utilizado en el batch k de producto terminado p en el establecimiento
0 en caso contrario

$$v_{hafime} \leq x_{haf} \qquad \forall h \in H_{af}, a \in A_f, f, i \in I_{me}, m \in MR_{ae}, e \tag{32}$$

$$v_{hafime} \leq w_{ime} \qquad \forall h \in H_{af}, a \in A_f, f, i \in I_{me}, m \in MR_{ae}, e \tag{33}$$

Las Ecs. (32) y (33) implican la generación previa del lote *h* del animal *a* en el frigorífico *f* ($x_{haf} = 1$) y la generación del lote *i* de materia prima *m* en el establecimiento *e* ($w_{ime} = 1$), respectivamente, para que el lote *h* de animal pueda asignarse a algún lote *i* de materia prima en alguno de los establecimientos de la CS.

$$Qa_{hafime} \leq Qa_{af}^{\max} \cdot v_{hafime} \qquad \forall h \in H_{af}, a \in A_f, f, i \in I_{me}, m \in MR_{ae}, e \tag{34}$$

La Ec. (34) establece que la cantidad Qa_{hafime} está acotada por la cantidad máxima de animal que se puede procesar en el frigorífico.

$$y_{imckpe} \leq w_{ime} \qquad \forall i \in I_{me}, m \in MS_{ce}, c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{35}$$

$$y_{imckpe} \leq z_{kpe} \qquad \forall i \in I_{me}, m \in MS_{ce}, c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{36}$$

Si no se genera el batch *i* de materia prima *m* ($w_{ime} = 0$) o no se genera el batch *k* de producto *p* en el establecimiento *e* ($z_{kpe} = 0$), la variable binaria y_{imckpe} será nula, de acuerdo con las Ecs. (35) y (36), respectivamente.

$$Qmcp_{imckpe} \leq Qcomp_{ce}^{\max} \cdot y_{imckpe} \qquad \forall i \in I_{me}, m \in MS_{ce}, c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{37}$$

$$\sum_{p \in PS_{ce}} \sum_{k \in K_{pe}} Qmcp_{imckpe} = Qm_{imce} \qquad \forall i \in I_{me}, m \in MS_{ce}, c \in C_e, e \tag{38}$$

$$\sum_{m \in MS_{ce}} \sum_{i \in I_{me}} Qmcp_{imckpe} = Qc_{ckpe} \qquad \forall c \in CR_{pe}, k \in K_{pe}, p \in P_e, e \tag{39}$$

Las Ecs. (37) a (39) vinculan a la variable continua $Qmcp_{imckpe}$ definida para rastrear el lote *i* de materia prima *m* que forma parte del lote *k* de producto final *p* en el establecimiento *e* con la variable binaria y_{imckpe} y las cantidades tanto de materia prima *m* que se transforma en componente *c* como con la cantidad de componente *c* que se utiliza para elaborar el producto *p*.

3.5 Función Objetivo

$$FO = \sum_{e} \sum_{m \in MS_{ce}} \sum_{i \in I_{me}} \sum_{c \in CR_{pe}} \sum_{p \in P_e} \sum_{k \in K_{pe}} y_{imckpe} + \sum_{f} \sum_{a \in A_f} \sum_{h \in H_{af}} \sum_{e} \sum_{m \in MR_{ae}} \sum_{i \in I_{me}} v_{hafime} \tag{40}$$

La función objetivo del problema planteado consiste en minimizar la dispersión de los lotes en toda la CSC.

4 Caso de Estudio

El caso de estudio planteado para la aplicación del modelo propuesto considera una CSC formada por tres frigoríficos ($F = 3$), dos establecimientos productores ($E = 2$) y

tres minoristas (R =3). Además, se contempla la faena de 2 tipos de animales (A = 2) y la elaboración de 12 productos distintos (P = 12), a saber: chorizo puro cerdo (p1), salame (p2), chorizo de segunda calidad o mezcla (p3), mortadela (p4), salchicha de viena (p5), jamón cocido (p6), morcilla (p7), queso de cerdo (p8), longaniza (p9), bondiola (p10), lomito (p11) y panceta (p12). Para la elaboración de dichos productos se consideran siete materias primas (M =7) que representan los principales cortes de carne de los animales mencionados y trece componentes (C = 13) que corresponden a los subcortes de las materias primas.

En el frigorífico f1 se faenan cerdos (a1), en f2 vacas (a2) y en f3 las dos especies (a1 y a2). A su vez, para cada frigorífico se propone el número máximo de lotes a saber: H_{f1} = 5 para f1, H_{f2} = 3 para f2 y H_{f3} = 4 para f3. En cuanto a los establecimientos, e1 elabora los productos p1, p2, p3, p4, p7, p8 y p9 (P_{e1} = 7) mientras que e2 elabora p2, p3, p4, p5, p6, p10, p11 y p12 (P_{e2} = 8). El número máximo de lotes i de materia prima y k de producto terminado propuestos son, I = 5 y K = 4, respectivamente, en ambos establecimientos.

En la Tabla 1 se muestran los datos referidos a las proporciones tanto de materia prima proveniente de cada animal como de componente obtenido de cada materia prima. Las proporciones de componente usadas en la elaboración de cada producto y las demandas mensuales de los minoristas por cada uno se detallan en la Tabla 2.

Tabla 1. Datos de desarmado del animal y las materias primas.

	Pa_{am}		Pm_{mc}												
M	a1	a2	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13
m1	0.18		0.25	0.75											
m2	0.13				0.50						0.42	0.08			
m3		0.17				0.30	0.70								
m4	0.07							0.20	0.80						
m5	0.14									0.38					0.62
m6	0.17												0.07	0.33	0.60
m7	0.13														1.00

Tabla 2. Demandas y datos para el armado de cada producto.

	Pc_{cp}													D_{pr} (kg)		
p	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	r1	r2	r3
p1	0.35	0.40	0.25											100	0	0
p2	0.30	0.50	0.20											200	100	100
p3		0.45	0..25	0.30										300	100	200
p4	0.20		0.10	0.30	0..40									2000	1000	800
p5	0.15	0.30	0.35		0.20									3000	1700	0
p6	0.20	0.60	0.20											2000	1000	900
p7							0.10		0.50				0.40	1000	0	0
p8									0.50				0.50	0	0	750
p9						0.25				0.25			0.50	0	0	800
p10								1.00						0	3500	0
p11											1.00			0	1200	0
p12												1.00		0	1500	0

El modelo MILP presentado fue implementado y resuelto en el software GAMS 31.1.1 en un procesador Intel(R) Core i7-10700, 2.9GHz empleando el código CPLEX 12.10. El problema involucra 6.527 ecuaciones con 3.924 variables continuas y 1.685 variables binarias. El tiempo de resolución es de 13,58 CPU s con una diferencia de integralidad de 3%. En la solución óptima, el valor de la función objetivo para la dispersión de los lotes es 100, lo que significa que los 10 lotes *h* de los 2 tipos de animal generados en los frigoríficos 1 y 3, se dispersan en 30 lotes *i* de materias primas los que, a su vez, forman parte de 19 lotes *k* de producto final en los 2 establecimientos.

En la Fig. 2 se ilustran los resultados obtenidos donde se pueden apreciar los lotes generados tanto para cada animal en los 2 frigoríficos utilizados como para las materias primas y productos de los 2 establecimientos productores, así como su dispersión a lo largo de toda la CSC. En la Tabla 3 se presenta un detalle de las cantidades de cada lote de animal enviado a cada establecimiento para formar los distintos lotes de materia prima mientras que en las Tablas 4 y 5 se reportan las cantidades de cada lote de producto enviadas a cada minorista por parte de los establecimientos 1 y 2 respectivamente.

Como se planteó anteriormente, el modelo desarrollado permite identificar el lote de animal con el que se elabora cada producto. Si se rastrea, por ejemplo, el chorizo de segunda calidad (p3) en la Fig. 2, se puede ver que la demanda total de los tres minoristas se cumple generando un único lote (k1) en el establecimiento 2 utilizando para su producción, 270 kg de c2 provenientes del batch i1 de m1, 150 kg de c3 aportados por el lote i1 de m2 y 180 kg de c4 generados a partir del batch i1 de m3. A su vez, en la Tabla 3, se puede observar que el lote i1 de m1 se genera a partir del lote h3 de cerdo (a1) proveniente de f1 y del lote h4 de f3, el lote i1 de m2 es generado por el lote h2 de f3 y el lote i1 de m3 proviene del lote h2 de vaca (a2) de f3. Si bien el lote i1 de m2 podría generarse utilizando lotes de un mismo frigorífico, con el fin de minimizar la dispersión y generar las cantidades exactas de componente, es que se produce esta situación. Cabe aclarar que, en este problema, no estamos considerando los costos, por lo cual, para el modelo es indistinto elegir entre lotes de un frigorífico u otro, pues lo que se busca es minimizar la dispersión.

5 Conclusiones

En este trabajo se ha propuesto un modelo MILP para resolver del problema de dispersión por lotes en la CSC con el fin de optimizar su trazabilidad a lo largo de la misma.

Se estudió una CSC compuesta por 3 niveles: frigoríficos que faenan varios animales, establecimientos que elaboran diferentes productos cárnicos y los minoristas que los demandan. La formulación desarrollada permitió determinar tipo y cantidad de animal que provee cada frigorífico, el número y tamaño de los lotes generados y la cantidad de los mismos que se envía a cada planta. A su vez, en estas últimas se decide qué materias primas y productos procesar, con qué número y tamaño de lote, respectivamente, y se establece la cantidad de componente intermedio producido y con qué lote/s de producto y cantidad del mismo se abastece la demanda de los minoristas. Asimismo, al minimizar la suma de las dispersiones de todos los lotes de animal, materias primas

y productos en la CSC el modelo propuesto minimiza, en caso de ocurrir algún problema con los lotes de algún producto, los costos de retirada del mercado de los mismos.

El caso de estudio presentado evidencia la capacidad del modelo de abordar la trazabilidad en la CSC mediante un enfoque integrado, al dimensionar los lotes para cada eslabón de la CS, al mismo tiempo que se resuelve el problema de la dispersión.

En trabajos futuros, se pretende desarrollar una formulación multiobjetivo en la que se incorpore el costo total de la CSC como criterio de desempeño adicional.

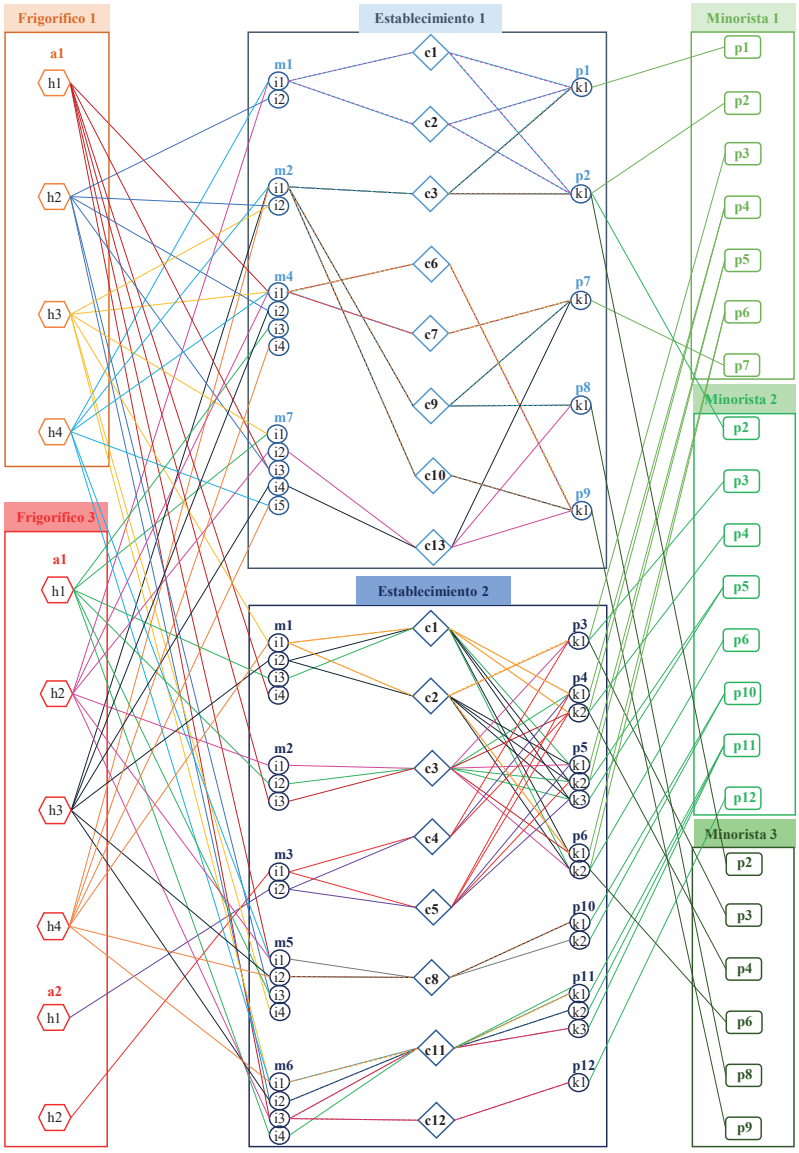

Fig. 2. Resultados para la CSC objeto de estudio.

Tabla 3. Cantidad de animal que forma parte de cada lote de materia prima en cada establecimiento de la CS.

		Qa_{hafime}(kg)									
		f1				f3					
		a1				a1				a2	
		h1	h2	h3	h4	h1	h2	h3	h4	h1	h2
Establecimiento 1											
m1	i1				1135.9		3528.4				
	i2		1764.2								
m2	i1				820.4			2548.3	1728.0		
	i2		1274.2	1274.2							
m4	i1	686.1		686.1	441.7		1372.2				
	i2		686.1					1372.2			
	i3					1372.2					
	i4								930.5		
m7	i1			1274.2		2548.3					
	i2						2548.3				
	i3	1274.2	1274.2								
	i4							2548.3			
	i5				820.4				1728.0		
Establecimiento 2											
m1	i1			1764.2					2392.6		
	i2							3528.5			
	i3					3528.5					
	i4	1764.2									
m2	i1						2548.3				
	i2					2548.3					
	i3	1274.2									
m3	i1										2742.9
	i2									2742.9	
m5	i1	1372.2			883.5		2744.4				
	i2							2744.4	1860.9		
	i3		1372.2			2744.4		3332.4			
	i4			1372.2							
m6	i1			1666.2	1072.8				2259.7		
	i2		1666.2								
	i3	1666.2					3332.4				
	i4					3332.4					

Tabla 4. Valores de Qp_{kper} para el establecimiento 1.

	Qp_{kper} (kg)				
	Establecimiento 1				
	p1	p2	p7	p8	p9
	k1	k1	k1	k1	k1
r1	100	200	1200		
r2		100			
r3		100		750	1000

Tabla 5. Valores de Qp_{kper} para el establecimiento 2.

	Qp_{kper} (kg)							
	Establecimiento 2							
	p3	p4		p5			p6	
	k1	k1	k2	k1	k2	k3	k1	k2
r1	300	1900	100	2000	1000		1950	50
r2	100		1000		1000	700		1000
r3	200		800					900
	p12			p11			p10	
	k1			k1	k2	k3	k1	k2
r1								
r2	1600			583.2	308.4	308.4	1750	1750
r3								

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Ajuste de parámetros cinéticos de la hidrogenación de CO_2 en presencia de metano

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Resumen. Con el propósito de modelar detalladamente un proceso de producción de metanol modificado para aceptar gas natural con un alto contenido de CO_2 (50-60%) como alimentación, se estudió la reacción de hidrogenación de CO_2 sobre un catalizador comercial de Ni. Se comprobó la simultaneidad de la reacción de reformado seco (RS) con la hidrogenación de CO_2 (RWGS) a 600ºC y 1,62 bar, empleando una mezcla $H_2/CO_2/CH_4$. Se intentó utilizar la información experimental para realizar por vía computacional el ajuste de los parámetros cinéticos de ecuaciones tipo LH-HW para RWGS y ley de la potencia para RS. Con la primera surgieron problemas de sensibilidad e ineficiencia lo que llevo a adoptar modelos tipo ley de potencia para ambas reacciones. Se facilitó la estimación de los parámetros iniciales para RS en razón del limitado grado de avance de esta reacción De este modo, se obtuvieron resultados satisfactorios, particularmente para RS, pudiéndose detectar los valores atípicos previamente a reiterar la predicción de los parámetros. Será necesario realizar experimentación adicional para mejorar el modelado de la reacción RWGS, si se pretende la simulación rigurosa y control global del proceso de interés.

Palabras clave: Metano, CO_2, Cinética, RWGS

1 Introducción

El metanol es una importante materia prima primaria para la energía y las industrias químicas, debido a su amplia gama de aplicaciones. Puede ser utilizado como combustible o para producir formaldehído, olefinas, ácido acético, ésteres, biodiesel, etc. Para la producción de metanol, se requiere la generación de gas de síntesis (syngas), que es una mezcla que contiene esencialmente H_2, CO y CO_2, en proporciones adecuadas. La generación de syngas se logra mediante la aplicación del conocido proceso de steam reforming (SR) aplicado al gas natural. Este proceso opera a alta temperatura (850-900ºC) y dado el carácter endotérmico de la reacción tiene un alto consumo energético dando origen a significativas emisiones de CO_2. Como alternativa en la última década

se han intensificado los estudios de diferentes procesos que usan como materia prima CO_2 cuya hidrogenación (a ≈ 600ºC) da lugar al gas de síntesis. La implementación a escala industrial de estos procesos se encuentra limitada por el alto costo del H_2, si es producido mediante procesos electrolíticos para evitar la generación de CO_2.

En estudios previos [1,2] se ha demostrado que una opción válida, desde el punto de vista técnico y económico, es la utilización de gas natural con alto contenido de CO_2 como materia prima. Mediante el proceso de reformado combinado (RC), es decir haciendo uso simultáneo de las reacciones de SR y reformado seco (RS) se logra generar syngas a menor costo y consumo energético. En nuestro país existen numerosos yacimientos de gas natural con alto contenido de CO_2, justificando su eventual utilización para producir metanol. Sin embargo, cuando el contenido de CO_2 es superior al 30%, es necesario reducir la concentración de CO_2 para mantener las ventajas mencionadas. En Cañete et al. [3,4] se demostró que la disponibilidad de yacimientos de gas natural con alto contenido de CO_2 (50-60%) permiten la generación de gas de síntesis para la producción de metanol mediante la introducción de un reactor de hidrogenación de CO_2 (RWGS), antes del reformador.

En esos estudios la simulación de dicho reactor se efectuó utilizando un modelo cinético reportado por Joo [5] para un catalizador (Fe_2O_3/Cr_2O_3) del tipo empleado en la reacción de gas de agua (WGS). Este catalizador no es adecuado para la reacción RWGS a alta temperatura (>400ºC) con exceso de H_2. Con el objeto de diseñar y simular rigurosamente el proceso, y ante la ausencia de expresiones cinéticas para la reacción RWGS en presencia de CH_4, hemos efectuado el estudio cinético de un catalizador comercial de Ni. Se resume aquí el trabajo experimental y la metodología empleada para obtener los parámetros cinéticos correspondientes.

En la Sección 2 se plantean los modelos cinéticos y los balances de masa correspondientes al sistema de ecuaciones diferenciales a resolver para el ajuste de parámetros. Posteriormente, en la Sección 3 se describen los equipos y la técnica empleada para la recolección de datos experimentales. En dicha sección referida a la metodología, también se presenta el esquema de optimización utilizado para resolver el problema de estimación de parámetros. En la sección siguiente se detallan los resultados obtenidos y los métodos de inicialización empleados en la búsqueda de parámetros. Finalmente, la última sección está destinada a las conclusiones.

2 Modelamiento cinético

2.1 Antecedentes

En la década del 50, presumiblemente debido al advenimiento del cálculo computacional en el campo de la ingeniería química, el modelado de velocidades de reacción en catálisis heterogénea tuvo un gran impulso, habiéndose estudiado variadas técnicas de determinación y análisis de los parámetros. En Kittrell y Mezaki [6] se describen modelos cinéticos y métodos clásicos de construcción. Los autores advierten que, en muchos casos, las conclusiones deben extraerse de conjuntos pequeños de datos cinéticos poco claros y por ende enfatizan la importancia del adecuado diseño experimental para

evitar conclusiones ambiguas. Una eficiente estrategia experimental recomendada involucra realizar una iteración continua entre el modelado computacional y la experimentación dentro del laboratorio. Por su parte, Seinfeld [7] enfatiza el uso de estimaciones no lineales para encontrar parámetros cinéticos a partir de datos de reactores experimentales, discutiendo en forma teórica la exactitud de los estimados en ecuaciones diferenciales ordinarias (ODEs). Este autor afirma que es necesario computar el coeficiente de sensibilidad correspondiente.

Los estudios cinéticos hasta la fecha abarcan numerosas reacciones heterogéneas de interés industrial, entre las que se puede mencionar particularmente el reformado de CH_4 con vapor de H_2O sobre catalizadores de Ni. Al-Ubaid [8] caracterizó dichos catalizadores. Aunque hay estudios cinéticos anteriores, cabe citar el realizado en nuestro país por Agnelli et al. [9]. Los autores utilizando un catalizador comercial de Ni estudiaron la reacción a diferentes temperaturas hasta 750ºC. Demostraron claramente que a esa temperatura la reacción de reformado va acompañada de la reacción WGS, siendo esta última cercana al equilibrio. Esta situación complica la obtención de los parámetros cinéticos. Aunque plantearon diferentes modelos cinéticos, concluyeron que la reacción puede simplificarse asumiendo que es de primer orden respecto al CH_4. Xu y Froment [10] reportaron ecuaciones cinéticas útiles para el diseño, simulación y optimización de un reformador industrial que aún son utilizadas. Vista la simultaneidad de las reacciones de reformado y WGS, ya reportada por Agnelli et al. [9], como así también la de metanación, los autores estudiaron las reacciones por separado, en diferentes rangos de temperatura. A baja temperatura (300-400ºC) se determinaron los parámetros cinéticos de la reacción RWGS y de metanación y a mayor temperatura (400-575ºC), los de SR. Derivaron una gran cantidad de modelos cinéticos para estas reacciones, asumiendo diferentes etapas elementales, por el conocido método Langmuir- Hinshelwood- Hougen- Watson (LH-HW). El ajuste final de parámetros se realizó empleando los datos experimentales obtenidos a todas las temperaturas.

Posteriormente, Hou y Hughes [11] estudiaron la reacción SR sobre Ni/α-Al_2O separando también en diferentes intervalos de temperatura la reacción principal de RWGS. Los resultados experimentales de conversión de CH_4 y CO_2 en función de W/F se correlacionaron mediante polinomios, y se obtuvieron las correspondientes velocidades de reacción por derivación. Se plantearon seis modelos cinéticos, asumiendo diferentes etapas elementales con bastante similitud con el tratamiento de Xu y Froment [10]. Los parámetros cinéticos óptimos se obtuvieron aplicando el método de cuadrados mínimos a la diferencia entre las velocidades de reacción experimentales y las estimadas por el modelo. Los autores mencionan que las diferencias observadas con el modelado de Xu y Froment [10], se deben a características del catalizador. Recientemente, Meloni et al. [12] ofrecen un panorama general de los aspectos más relevantes del proceso de SR incluyendo detalles de diferentes catalizadores de Ni. y sus condiciones operativas.

Es sabido que el catalizador a base de Ni utilizado comúnmente para el reformado con vapor también cataliza la reacción inversa del gas de agua (RWGS) y no presenta desactivación a corto plazo cuando se alimenta CO_2 e H_2 a baja temperatura, como demostraron Xu y Froment [10] y Hou y Hughes [11]. Por tal motivo y debido a su bajo costo comparado con catalizadores basados en metales nobles, se ha seleccionado un

catalizador comercial de Ni para realizar las experiencias y a partir de ellas estimar los parámetros cinéticos.

La bibliografía específica sobre el modelado cinético de la reacción RWGS es escasa y relativamente reciente. Wolf et al. [13] afirmaron que el catalizador de Ni es capaz de catalizar la reacción RWGS en forma muy efectiva, trabajando a 900º C. A esta temperatura la presencia de CH_4, debido a la metanación del CO, es muy baja. Los autores desarrollaron un modelo cinético del tipo ley de la potencia, trabajando en primer lugar a baja conversión para determinar el orden de reacción del CO_2 y del H_2. Los resultados fueron 1 y 0,3 respectivamente. Dicha expresión fue complementada con un término de retroceso imponiendo la condición de reacción nula en el equilibrio. Para la reacción de WGS a baja temperatura, Maklavany et al. [14] estimaron los parámetros cinéticos de una expresión tipo ley de potencia. Aunque este trabajo no se refiere a RWGS y se utiliza un catalizador $CuO/ZnO/Al_2O_3$, es oportuno citarlo porque discute en mayor detalle el método computacional utilizado para la estimación de los parámetros y su validación. Más relevante para nuestros objetivos es el estudio de Vidal Vazquez et al. [15], quienes utilizaron los modelos cinéticos de Xu y Froment [10] y Hou y Hughes [11] como así también una expresión basada en la adsorción molecular de reactivos y productos, siendo la siguiente reacción en superficie la etapa controlante: $CO_2.S + H_2.S \leftrightarrow CO.S + H_2O .S$

De esta forma se obtiene una ecuación con un denominador cuadrático que involucra las constantes de adsorción de CO_2, H_2, H_2O y CO. La reacción de hidrogenación de CO_2 y la de metanación se estudiaron en el rango 550 -850ºC a presión atmosférica y 30 bar, empleando catalizadores de Ni y de Rh. Los autores demostraron que el modelo propuesto por Xu y Froment [10] es el mejor para representar el comportamiento de los catalizadores estudiados. La revisión bibliográfica resumida aquí demuestra que no existen estudios cinéticos previos sobre RWGS en presencia de CH_4.

2.2 Reacciones intervinientes

Al combinarse GN con alto contenido de CO_2 e H_2 se produce la reacción RWGS:

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

Además, la combinación de metano con CO_2 puede dar lugar a la reacción RS:

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$$

Asumimos que el reactor tubular de lecho fijo es isotérmico, opera en estado estacionario y corresponde al modelo homogéneo en una dimensión. En este caso, el balance de masa puede expresarse con la Ec. 1, donde F_i^0 es el caudal inicial de alimentación del *i*-ésimo componente, X_i es la conversión del componente *i*, W es la masa de catalizador expresada en gramos y r_i es la velocidad de reacción del *i*-ésimo componente.

$$F_i^0 \frac{dX_i}{dW} = r_i \quad (1)$$

Dado que se producen simultáneamente la reacción RWGS y de RS, la Ec. 1 se aplica al CO_2 y al CH_4. El sistema de ecuaciones que representa este proceso corresponde a

las Ecs. 2 y 3. En ambos casos se han asumido expresiones del tipo ley de la potencia. En dichas ecuaciones, p_i es la presión parcial del *i*-ésimo componente, k_{fRWGS} y k_{fRS} son las constantes cinéticas de la reacción de avance y K_{RWGS} es la constante de equilibrio termodinámico. Las presiones parciales se calculan como $p_i = P\,Y_i$, donde P es la presión total e Y_i es la fracción molar del *i*-ésimo reactivo.

$$F_{CO2}^{0}\frac{dX_{CO_2}}{d(\mathrm{W})} = k_{fRWGS}{p_{CO_2}}^{a}{p_{H_2}}^{b}{p_{CO}}^{c}{p_{H_2O}}^{d}\left(1-\frac{p_{CO}\,p_{H_2O}}{K_{RWGS}\,p_{CO_2}\,p_{H_2}}\right)+k_{fRS}\,p_{CH_4}^{e}\;p_{CO_2}^{f}{p_{CO}}^{g}{p_{H_2}}^{h} \quad (2)$$

$$F_{CH_4}^{0}\frac{dX_{CH_4}}{dW} = k_{fRS}{p_{CH_4}}^{e}{p_{CO_2}}^{f}{p_{CO}}^{g}{p_{H_2}}^{h} \quad (3)$$

En la Ec. 3 se ha eliminado el paréntesis que contiene la constante de equilibrio porque la conversión máxima de esta reacción es de 15% en nuestras condiciones operativas.

3 Metodología

En las Ecs. 2 y 3, se desea ajustar simultáneamente los siguientes diez parámetros cinéticos: todos los órdenes de reacción *a, b, c, d, e, f, g* y *h*, junto con ambas constantes cinéticas k_{fRWGS} y k_{fRS}. Cabe aclarar que la constante termodinámica K_{RWGS}, no es un parámetro de ajuste (no se hicieron mediciones en condición de equilibrio). Con los datos obtenidos experimentalmente para el catalizador de Ni, el ajuste de dichos parámetros se realizó resolviendo el sistema de ecuaciones mediante técnicas de optimización multivariable.

3.1 Sección Experimental

La obtención de datos experimentales fue llevada a cabo en un reactor conformado por un tubo de cuarzo de 1 metro de longitud y 4 mm de diámetro ubicado en el interior de un horno eléctrico Lindberg-Blue M, el cual posee 3 zonas de calentamiento independiente. El reactor se encuentra alimentado por tubos de gas de CH_4, H_2, CO_2 y Ar regulados por un controlador y sus respectivos caudalímetros másicos. La corriente de salida del horno es alimentada a una trampa de agua, que es un lecho fijo de sílica gel y tamiz molecular. Posteriormente, es analizada en un cromatógrafo gaseoso Perkin Elmer Autosystem que opera con un detector de conductividad térmica (TCD). La temperatura del lecho de catalizador (600º C) fue determinada con una termocupla tipo K colocada a la salida del lecho de catalizador y la presión con un manómetro de baja presión (1,6 bar). Un esquema del equipamiento empleado se muestra en la Figura 1. Previo a cada experiencia, el catalizador fresco es reducido con una corriente de hidrógeno durante media hora a una temperatura de 500°C. Posteriormente, luego del inicio de la reacción, el sistema es monitoreado durante 2 o 3 horas para asegurar que las mediciones de composición de los productos correspondan al estado estacionario.

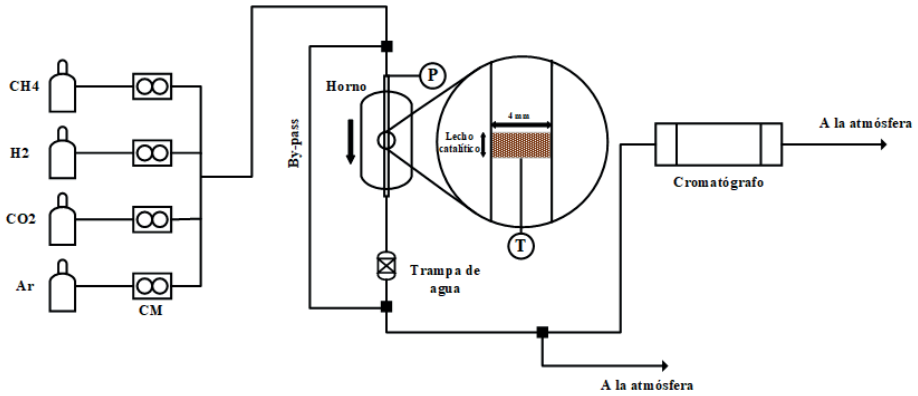

Fig. 1. Diagrama de flujo del equipo empleado.

Debido a su bajo costo y disponibilidad, se decidió utilizar un catalizador comercial de Ni del tipo empleado en el reformado de CH_4 con vapor de agua: Ni (9%)/Al_2O_3. Las pastillas de catalizador se molieron hasta alcanzar un diámetro promedio de 0,3 mm para minimizar efectos difusionales. La ausencia de resistencia a la transferencia de masa interna y a la transferencia de calor fue verificada empleando criterios conocidos [16]. Se utilizaron para el conjunto de experiencias, masas de catalizador en el rango 10-70 mg. Con estas cantidades de sólido la longitud de lecho osciló entre 0,2 y 1,4 cm. Se investigó el comportamiento de distintas mezclas en un rango de caudal de 135-144 cm^3/min. Las 6 composiciones de alimentación y las cargas de catalizador empleadas se muestran en la Fig. 2.

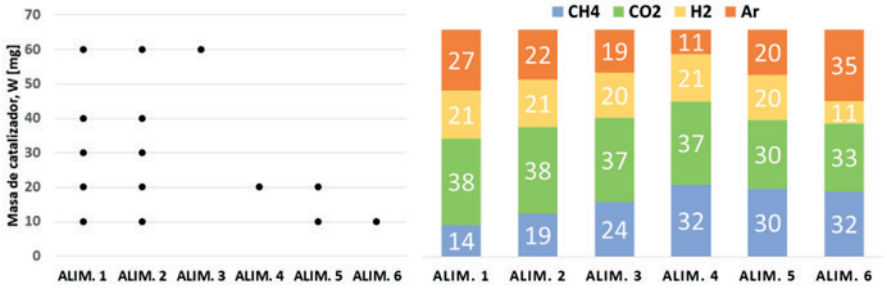

Fig. 2. Composición volumétrica de cada alimentación y cargas de catalizador empleadas en los ensayos experimentales.

Se realizaron 15 experiencias, las que permitieron obtener conversiones de CH_4 entre 3,5 y 16%, y conversiones de CO_2 en el rango 22-31%. Para las composiciones de alimentación seleccionadas, el análisis de equilibrio termodinámico predice conversiones de CH_4 de 69 a 75% y de CO_2 entre 38 y 52%. Por lo tanto, los valores experimentales indican que la reacción predominante es RWGS.

3.2 Estimación de parámetros cinéticos

Este caso se puede abordar como un problema de optimización multivariable no restringida. Vistos el modelo cinético propuesto y las composiciones de la alimentación, donde las derivadas son iguales a cero en el punto inicial, los métodos de optimización con gradientes diferenciales no se aconsejan. Por tal motivo, para la optimización se eligió un método libre de derivadas denominado Simplex Nelder Mead [17].

Los parámetros cinéticos conforman el siguiente vector de variables de optimización: $z^T = [k_{fRWGS}, k_{fRS}, a, b, c, d, e, f, g, h]$. Como se muestra en la Fig. 3, el optimizador se encuentra acoplado a un resolvedor de ecuaciones diferenciales ordinarias (ODEs) con un método explícito Runge-Kutta de segundo y tercer orden [18,19]. Este procedimiento se emplea para resolver el sistema de ecuaciones comprendido por las Ecs. 2 y 3.

Por su parte, el optimizador compara las conversiones predichas por dicho modelo con las experimentales. En el sentido de cuadrados mínimos, la función objetivo OF a minimizar se puede expresar (Ec. 4) como la sumatoria de las diferencias para cada punto obtenido entre las conversiones de CO_2 y CH_4 predichas X_i y experimentales $\hat{X}_i$.

$$OF = mín \sum \left(X_i - \hat{X}_i\right)^2 \tag{4}$$

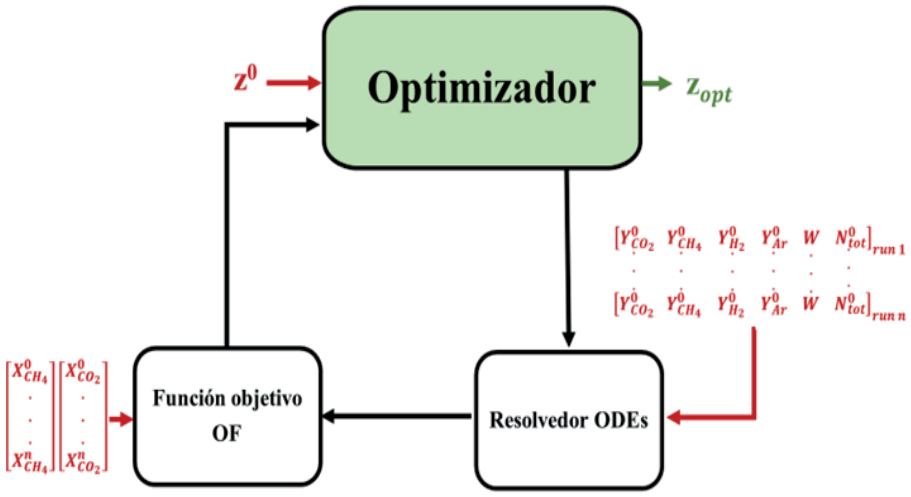

Fig. 3. Esquema del método de optimización de parámetros cinéticos

Para determinar las bondades del ajuste se calculó el error porcentual absoluto medio (MAPE) para ambos componentes (Ec. 5). En esta ecuación n es el número de experiencias realizadas.

$$MAPE_i = \frac{1}{n} \sum_1^n \left| \frac{(X_i - \hat{X}_i)}{X_i} \right| 100 \tag{5}$$

El método de Nelder-Mead empleado, cuyo algoritmo está explicado en detalle en [17], es un método de búsqueda directa que sirve para optimización multidimensional sin restricciones, sin emplear información sobre derivadas (ni explícitas ni implícitas). Mediante su aplicación, tuvimos éxito para resolver nuestro problema de interés, mientras que usando la bien conocida técnica de búsqueda Levenberg-Marquardt [20], la cual emplea Jacobianos en su algoritmo, no hemos logrado arribar a una solución completamente satisfactoria con su parámetro de ajuste fijado en $\mu_k = 10^{-2}$.

Dado que Nelder-Mead no usa derivadas, es menos probable que quede atrapado en un mínimo local, en comparación con Levenberg-Marquardt. Esta característica podría ser la razón del mejor desempeño observado del algoritmo Nelder Mead. Dicho método fue eficaz, pero demostró ser bastante lento y fuertemente dependiente del punto inicial. Por esta razón, sería interesante continuar explorando en detalle otras alternativas. Sabemos que Levenberg-Marquardt es una técnica standard especialmente robusta y ampliamente usada para la minimización de funciones del tipo cuadrados mínimos. Por lo tanto, para lograr mayor efectividad, se investigará una estrategia adecuada para elegir μ_k en el algoritmo clásico de Levenberg-Marquardt pues, en la práctica, este parámetro modifica el subproblema de cuadrados mínimos lineales a resolver.

Por otra parte, el estudio del comportamiento de las técnicas metaheurísticas ante estos problemas es un tema de investigación abierto. Dichas técnicas, por ejemplo Algoritmos Genéticos u Optimización con Enjambre de Partículas, exploran eficientemente grandes espacios de búsqueda y podrían constituir alternativas útiles. Se las suele utilizar cuando no existe un método exacto de resolución, cuando existe un método exacto que consume mucho tiempo para ofrecer la solución óptima, cuando existen limitaciones de tiempo o bien como paso intermedio para obtener una solución inicial para la aplicación de otra técnica. En tal sentido, como trabajo futuro, planificamos evaluar el comportamiento de una hiperheurística eficiente [21] ante este problema de ajuste de parámetros.

4 Resultados

En primera instancia, para la reacción de RWGS se evaluó la posibilidad de emplear una ecuación cinética del tipo LH-HW propuesta por Xu y Froment [10]. Para RS, por su menor grado de avance, se postuló la ley de potencia. Después de numerosos intentos no se lograron resultados satisfactorios ya que estos dependían fuertemente de los valores iniciales seleccionados.

Con el propósito de disminuir la complejidad numérica y evitar los problemas de sensibilidad inherentes al modelo LH-HW, se decidió adoptar expresiones cinéticas tipo ley de la potencia para ambas reacciones. (Ec. 2 y Ec. 3). Se aplicó el criterio de cuadrados mínimos utilizando diversos puntos iniciales, lo cual demandó excesivo tiempo de cómputo. Hemos observado que la fijación de cualquier conjunto de parámetros iniciales conduce a una convergencia extremadamente lenta. Este comportamiento indica la necesidad de adoptar algún método de selección de los valores iniciales estimados, o bien ciertos cambios en el diseño experimental [9, 22].

En nuestro caso, el contexto permite realizar ciertas suposiciones con el fin de obtener valores iniciales más cercanos. Así, teniendo en cuenta que el grado de avance de la reacción del RS es limitado, se puede asumir operación diferencial. Por lo tanto, la velocidad de reacción r_{RS} se calculó utilizando la Ec. 6, donde X_{CH_4} corresponde a la conversión experimental de CH_4, $F^0_{CH_4}$ el flujo molar inicial de CH_4 en mol/h y W es la masa de catalizador en gramos.

$$r_{RS} = \frac{X_{CH_4} F^0_{CH_4}}{W} \tag{6}$$

Además, se procedió a la linealización de la Ec. 3 mediante logaritmos obteniéndose la expresión de la Ec. 7.

$$\log r_{RS} = \log k_{RS} + e \log p_{CH_4} + f \log p_{CO_2} + g \log p_{CO} + h \log p_{H_2} \tag{7}$$

Las presiones parciales utilizadas en la Ec. 6 fueron calculadas como un promedio entre las presiones de entrada y las de salida. Así, utilizando los 15 datos experimentales disponibles, se realizó el ajuste de parámetros por cuadrados mínimos entre el $\log r_{RS}$ experimental y el predicho por el modelo.

Tabla 1. Valores iniciales obtenidos por reformulación de la Ec. 3

k_{RS}	e	f	g	h	MAPE [%]
0,290	0,574	1,574	-0,737	-0,820	4,92

En particular, los valores obtenidos en la Tabla 1 fueron utilizados como punto de inicialización para la optimización del problema completo. El optimizador convergió a los parámetros reportados en la primera fila de las Tablas 2 y 3.Los valores corresponden a las masas de catalizador expresadas en gramos, las presiones parciales, en bar y el caudal $F^0_{CO_2}$, en mol/h.

Tabla 2. Parámetros cinéticos estimados para RWGS.

¿Con Valores atípicos?	k_{fRWGS}	a	b	c	d
SI	0,14	1,43	1,07	-1,13	-1,16
NO	0,06	0,59	0,61	-0,65	-1,47

Tabla 3. Parámetros cinéticos estimados para RS

¿Con Valores atípicos?	k_{fRS}	e	f	g	h
SI	0,08	0,47	1,05	-0,48	-0,82
NO	0,043±0,006	0,386±0,003	0,731±0,055	-0,702±0,082	-0,685±0,031

Dada la limitada cantidad de datos experimentales, en nuestro caso ha sido imposible identificar a priori los valores experimentales atípicos (outliers), pues las técnicas existentes para su detección previa [23] son inherentemente estadísticas. Una vez realizado un primer ajuste de parámetros, dichos valores recién pudieron ser detectados comparando las conversiones experimentales de CO_2 y CH_4 versus las predichas por el modelo. En la Fig. 4 puede observarse la existencia de valores atípicos, indicados como los puntos A, B y C.

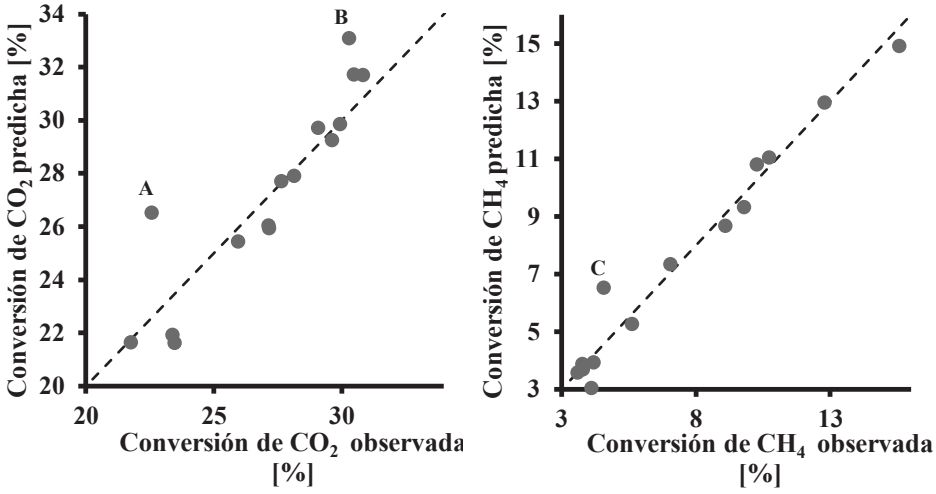

Fig. 4. - Gráficos de paridad.

Al eliminar los tres outliers y realizar nuevamente el ajuste de parámetros, se obtuvieron los resultados que se muestran en la última fila de las Tablas 2 y 3. Esta combinación de parámetros es la más confiable que hemos podido hallar hasta el presente, con un MAPE asociado menor al 7%.

A los efectos de acotar el valor de estos parámetros se procedió a la determinación de los intervalos de confianza. Para esto se utilizaron los resultados de 39 ajustes, realizados con diferentes valores iniciales, que permitieron el cálculo de la desviación standard. Para la reacción de RS se obtuvieron los valores máximos y mínimos que se muestran en la Tabla 3. Se puede apreciar que la menor diferencia se obtuvo en el orden de reacción para el CH_4 reactante cuya concentración fue modificada en un rango mas amplio (ver Figura 2). Cuando se realizó el mismo trabajo para RWGS el rango de variación de los parámetros fue excesivo (40-50%), y por esta razón no son informados. Este comportamiento se atribuye a condiciones del trabajo experimental. En primer término es evidente que el número de experiencias realizadas es reducido. Por otra parte, como se observa en la Figura 2, la concentración de CO_2 e H_2 se mantuvo prácticamente constante, por lo que es de esperar menor incidencia en la reacción RWGS. Además, la

conversión de CO_2 fue en la mayoría de las experiencias cercana al valor de equilibrio. Solo en 4 de las 15 corridas la diferencia entre la conversión de equilibrio y la experimental fue superior al 20%. Esta condición es el resultado de la velocidad espacial empleada. .Para obtener resultados más confiables será necesario: a) realizar un mayor número de experiencias explorando el efecto de los productos de reacción (CO y/o H_2O) en la alimentación, b) aumentar el caudal de alimentación para obtener conversiones de CO_2 más alejadas del valor de equilibrio y c) utilizar un mayor rango de concentraciones de H_2.

Utilizando los parámetros cinéticos obtenidos cabe estimar la velocidad de reacción de RWGS y RS a efectos comparativos. Para presiones parciales promedio entre los valores de entrada y salida, de una experiencia realizada con 30 mg de catalizador resulta: r_{RWGS} = 4,11 gmol CO_2 /gcat h; r_{RS} = 0,17 gmol CH_4/gcat h comprobándose que las ecuaciones cinéticas predicen la mayor actividad catalítica de la reacción de interés.

A 600ºC, Cui et al. [24] estudiaron la cinética de RS sobre un catalizador de Ni (8%)/α-Al_2O_3 utilizando una ecuación tipo ley de la potencia. Encontraron órdenes de reacción de 0,72 y 0,41 para el CH_4 y el CO_2, respectivamente. Para el H_2 el orden es prácticamente nulo y el de CO es -0,37. En nuestro caso, el orden de reacción del CH_4 es menor (0,39) y el de CO_2 es más elevado (0,73). Dado que el estudio fue realizado con presiones parciales muy bajas, la velocidad de reacción no es comparable. Como se ha mencionado anteriormente, no existen estudios de RWGS en presencia de CH_4 lo que impide un mejor análisis de nuestros resultados.

5 Conclusiones

Con el propósito de modelar detalladamente un proceso de producción de metanol modificado para aceptar gas natural con un alto contenido de CO_2 (50-60%) como alimentación, se estudió la reacción de hidrogenación de CO_2 sobre un catalizador comercial de reformado de Ni. En este manuscrito se analizan los datos recolectados experimentalmente, para luego realizar el ajuste de los parámetros cinéticos correspondientes. Se comprobó que se producen simultáneamente la reacción RWGS y la de reformado seco., siendo la primera la de mayor grado de avance.

Se investigó en primer lugar un modelo cinético propuesto en la literatura para la reacción de RWGS [10]. Mediante un análisis de sensibilidad, se detectaron las severas limitaciones del modelo referidas al efecto de las perturbaciones. Más aún, al efectuar el ajuste de datos, hemos observado que el problema de cómputo que surge de dicho modelo tiene problemas numéricos de estabilidad.

Dadas las dificultades numéricas inherentes al modelo L-H tradicional, se decidió recurrir a expresiones del tipo ley de la potencia para ambas reacciones. No se puede afirmar que existe una técnica general infalible para atacar el problema de estimación de parámetros mediante cuadrados mínimos no lineales. Hemos comprobado que la fijación de cualquier conjunto de parámetros iniciales es ineficiente pues la convergencia requiere un prohibitivo esfuerzo computacional. Para RS ha sido posible la linealización del modelo cinético para obtener valores iniciales aproximados. Esta técnica

condujo a un ajuste exitoso, solo para RS. En el caso de la reacción RWGS los parámetros obtenidos son solo aproximados, debido esencialmente a condiciones operativas de la experimentación que han sido identificadas y deberán ser modificadas. A continuación, se identificaron los valores atípicos que fueron removidos para lograr el ajuste final.

Dado que la metodología propuesta emplea la totalidad de la información experimental disponible con fines de ajuste, resulta necesaria una validación de los resultados con datos experimentales independientes. Por lo tanto, como trabajo futuro, se planifica efectuar algunos experimentos adicionales con el fin de validar los parámetros cinéticos hallados. A pesar de las dificultades encontradas, el ajuste con la ley de la potencia presentado aquí servirá para una primera estimación del tamaño y costo del reactor de hidrogenación si se optara por la utilización de un catalizador típico de reformado.

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Modelo de planificación de decisiones del desarrollo masivo de operaciones upstream

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Resumen. El trabajo presenta un modelo de tipo MILP que incluye alternativamente cuatro actividades típicas (perforación, terminación, fractura hidráulica y mantenimiento) en la industria del gas y petróleo. El mismo consiste en un núcleo común de ecuaciones que modelan el problema y una serie de restricciones específicas de las operaciones que se incluyen en el caso a resolver.

Palabras claves: Gas y Petróleo, Upstream, Planificación, Optimización.

1 Introducción

La administración óptima de las actividades en el sector upstream de la industria petrolera, es compleja y crítica para la rentabilidad del negocio. En yacimientos no convencionales (Vaca Muerta), se pueden realizar perforaciones de múltiples pozos con diferentes tipos de unidades de perforación. En equipos móviles, de tecnología más moderna, la limitante crítica es su disponibilidad (tipo y cantidad), mientras que, en equipos no móviles, que deben ser desmontados y vueltos a montar para su traslado, la restricción fuerte es el tiempo insumido en las operaciones.

Otra operación de relevancia es el mantenimiento de los pozos que están operativos (pulling). Esto se realiza con unidades móviles preparadas para izar las varillas del tubing de producción de cualquier tipo de pozo. Su uso más intensivo es en campos convencionales en recuperación primaria con problemas en la bomba de fondo, ya sean mecánicos o eléctricos. En grandes campos se puede tener simultáneamente del orden de cientos de pozos a reparar [1], por lo que planificar la actividad de pulling resulta muy complejo.

La Ingeniería de Sistemas de Procesos está teniendo un rol importante en estos temas. Varios trabajos abordan aspectos específicos de la planificación de decisiones en el upstream [2], [3], [4], etc., si bien las planillas de cálculo son aún muy utilizadas. A pesar de estos trabajos, la consideración integrada de los diferentes problemas de planeamiento de las múltiples actividades del upstream, aún no ha sido totalmente abordada en la literatura.

2 Modelo desarrollado

$$\text{Min } FO_1 \text{ o } FO_2 \text{ o } FO_3 \text{ o } FO_4$$
$$\text{Sujeto a:}$$
$$\{\text{Modelo núcleo de asignación y traslado de equipos}\}_{i,j,k,t} = 0$$
$$\{\text{Estimación de variables y función objetivo } (FO_{1,2,3,4})\}_{i,j,k,t} = 0$$
$$\{\text{Restricciones operativas y contractuales}\}^{OP}_{1,2,3,4} \leq 0$$

Sets (i: Equipos ; j:Pozos ; k: Secuencias ; t: Periodos.

El modelo considera la planificación, en un dado horizonte de tiempo, de decisiones económicas de las operaciones (monto de inversiones y plan de erogaciones, costos de infraestructura y operativos, ingresos por ventas de gas y petróleo, etc.), decisiones de diseño y uso de recursos (selección del tipo y cantidad de tecnologías de perforación y servicios, etc.) y operativas (orden y secuenciado de tareas, tiempos de ejecución, ruteo).

Se trata de un modelo de Programación Mixto Entera Lineal (MILP), que extiende trabajos previos de los autores [5]. Para su implementación y resolución se utiliza el programa de modelado y optimización GAMS (General Algebraic Modeling System) [6]. El modelo es de carácter general, adaptado para optimizar la planificación de cuatro operaciones en yacimientos convencionales o no convencionales. Estas son: (i) para el período de desarrollo del campo de pozos: perforación, terminación y fractura hidráulica, (ii) para el período de operación de los pozos: reparación y mantenimiento. El enfoque integral del modelo resulta ser particularmente adecuado en desarrollos donde una de las decisiones fundamentales a tomar es la selección óptima de equipos de perforación de torres móviles, como lo son los walking rigs y skidding rigs, entre otros. Se requiere información diferente para los cuatro escenarios de planificación de operaciones. Estos son: (i) OP1: perforación; (ii) OP2: fractura; (iii) OP3: perforación y fractura; (iv) OP4: Pulling y mantenimiento.

En OP1 (perforación), se utilizan datos de tiempo de ejecución, además de los costos fijos y variables que se solicitan en todos los casos. Sin embargo, no es relevante la distancia entre los pads, ni se considera producción luego de finalizada esa operación. En cambio, en OP4 (pulling + mantenimiento) si es relevante considerar la distancia entre pads y con ello se deben activar las restricciones de costo por distancia que penalizan la función objetivo. Esto se debe a los tipos de contrato que tienen las empresas con cada servicio y a las variables que impactan sobre los costos: la distancia entre operaciones, el tiempo de ejecución de cada secuencia, y la producción asociada a la ejecución. La producción a su vez, está asociada a parámetros de diseño del pozo tales como el número de etapas de fractura en pozos no convencionales, y el tipo de bomba y arreglo de fondo para los pozos convencionales. A su vez, el tiempo de ejecución, depende del largo del pozo y otras características de arquitectura que se pueden simplificar y calcular en el pre-procesamiento de los datos indicando únicamente el número de etapas productivas de cada pozo, junto con lo que produce cada etapa y lo que insume en tiempo de ejecución. Es decir, en la Operación 2 (fractura) se indica cuánto tiempo de operación se requiere para cada etapa de fractura que a su

vez corresponde a la longitud del tramo horizontal de la perforación y de esta manera se construye la estructura de costos y beneficios.

3 Caso de estudio (Operación 3: Perforación + fractura):

Se presenta un caso de estudio consistente en un proyecto de desarrollo y operación de pozos en un yacimiento no convencional, en el que se involucra el movimiento de diferentes tipos de equipos en una determinada área concesionada, para realizar actividades de perforación, tareas de terminación, y las operaciones de workover, involucradas en la fractura hidráulica de cada etapa del pozo, englobados en lo que llamamos OP3.

En el caso de estudio se opta entre 4 tecnologías de equipos de torre con métricas distintas, con el objetivo de perforar 8 pozos agrupados en 2 pads, cada uno de ellos con un diseño propio previamente definido en cuanto a número de etapas de fractura y largo del pozo. Los datos tales como costos, velocidades de operación, producción por pozo, etc., se obtuvieron de información típica de explotaciones en nuestro país en los últimos dos años, publicadas en portales oficiales de la Secretaria de Energía de La Nación. El horizonte de planeamiento considerado es de mediano plazo y con un tiempo discreto de 24 periodos o meses.

Como tecnologías de perforación se seleccionan y combinan varios tipos de los que se utilizan en nuestro país, cuyos parámetros DTM y ROP se muestran en la Tabla 1.

Tabla 1: Indicadores de performance (K.P.I.´s) de los equipos.

Tipo de Rig	Flex (i_1)	Walking (i_2)	Skidding (i_3)	Convencional (i_4)
DTM_1 (dentro del pad)*	2	1	1	15
DTM_2 (fuera del pad)*	7	15	15	15
ROP_1 (tramo vertical)*	156	140	120	120
ROP_2 (tramo horizontal)*	120	110	90	90

*DTM (Días de montaje y transporte); ROP (tasa de penetración del trepano, metros/día)

El modelo desarrollado y aplicado en este caso permite estudiar el diseño del conjunto de pozos prospectivos, la selección del proveedor de cada equipo y asignación de una serie de pozos a perforar por cada uno y sus rutas. Así mismo, se consideran diferentes funciones objetivo de tipo económico, de producción y de eficiencia operativa. Permite que el modelo minimice costos, minimice el makespan, o el tiempo total de actividades, y también permite maximizar ingresos, ganancias, valor presente o indicadores económicos más acordes al negocio como EBITDA o Breakeven-cost. Se considera la actividad de fractura hidráulica seguida inmediatamente a la perforación. Por simplicidad, se asume que todas las etapas de fractura se realizan con los mismos volúmenes de agua y arena y con el mismo tipo de terminación y con equipos idénticos lo que define costo y tiempo fijo para cada etapa junto con su producción por periodo esperada, para pozos de gas, en zonas altamente productivas. Los resultados de asignación y movimiento de los equipos del caso de estudio se muestran para cada

rig en la tabla 2 junto con las variables más relevantes para las 4 funciones objetivo propuestas.

Tabla 2. Resultados del caso de estudio. OP3: Perforación + Fractura

Corridas	FO_1 Max Ganancias	FO_2 Max Producción	FO_3 Min Costo	FO_4 Min Breakeven
Costo*	71.979	73.146	**67.344**	70.26
Ingreso*	128.044	128.044	110.67	125.936
Ganancias*	**56.065**	54.898	43.326	55.676
Producción*	753.2	**753.2**	651	740.8
Breakeven*	95.56	97.11	103.45	**94.84**
Rig_{i1}	j_1-j_{10}-j_9	j_1-j_{10}-j_9-j_6	-	j_1-j_{10}-j_9
Rig_{i2}	j_2-j_{12}-j_7	j_2-j_{12}-j_8	-	j_2-j_{11}
Rig_{i3}	j_3-j_5-j_8	j_3-j_5-j_7	j_3-j_5-j_6-j_7-j_8	j_3-j_5-j_8
Rig_{i4}	j_4-j_{11}-j_6	j_4-j_{11}	j_4-j_{10}-j_9-j_{12}-j_{11}	j_4-j_{12}-j_7-j_6

*Costo, ingreso y ganancias (10^6 U$S); Producción ($10^6 m^3_{gas}$); Breakeven (U$S/$10^3 m^3_{gas}$).

4 Conclusiones

Se presentó un modelo integral para gestión óptima de actividades típicas del sector upstream de la industria del gas y petróleo. La comparación de los resultados de las distintas FO demuestra la capacidad y flexibilidad del modelo para cubrir distintas estrategias de operación y objetivos del sector. La secuencia en que se intervienen los pozos cambia según la estrategia que se decida implementar por lo que se concluye que el modelo de asignación es de utilidad. Se alcanzan mejoras de 15% en la producción, 29% en las ganancias del proyecto y un corte de rentabilidad mínimo de 94.84 U$S por cada 1000 m^3 de gas en boca de pozo a un precio de 4.7 U$S / MM Btu.

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Propuesta de una biorrefinería en una industria azucarera cubana aprovechando la biomasa

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Resumen. La industria azucarera cubana abre posibilidades para el desarrollo de una biorrefinería por las características de sus corrientes y sus facilidades para la obtención de diferentes productos, coproductos y energía. En el presente trabajo se propone el desarrollo de una biorrefinería considerando la obtención de azúcar, energía, etanol, xilosa, torula en crema y biogás como productos principales, empleando como biomasa la caña y el bagazo sobrante. En la obtención de etanol de segunda generación se utilizan como fuentes azucaradas el hidrolizado de bagazo, el jugo de los filtros extraído de la producción azucarera y la melaza, lo que permite disminuir en un 24% el consumo de esta última en la etapa fermentativa. La ganancia del esquema propuesto fue optimizada considerando 120 y 150 días de zafra, obteniéndose que la producción de alcohol extrafino pueda aumentar a 800 y 900 hL/d respectivamente, manteniendo constante la producción de alcohol etílico rectificado. Al analizar económicamente los procesos, solo se logra rentabilidad de forma independiente en la producción de etanol, aunque el esquema integrado sí resulta rentable para los dos períodos de zafra analizados.

Palabras clave: biorrefinería, caña de azúcar, integración, factibilidad económica.

1 Introducción

Una definición de biorrefinería es: "una instalación donde, mediante diversos procesos de transformación de la biomasa, se genera bioenergía (calor, electricidad, biocombustibles) y un amplio espectro de bioproductos (materiales, productos químicos, alimentos y piensos), requiriéndose para ello la integración de diferentes procesos y tecnologías en una misma instalación". Diversos autores han estudiado los posibles esquemas de biorrefinería que se pueden adaptar a una industria azucarera, entre ellos [1]. En ellas puede existir un grado de flexibilidad en las capacidades de procesado, permitiendo la creación de una base de producción y coproducción biológica, sostenible económicamente en el concepto de biorrefinería, siendo sus principales productos azúcar, etanol y energía [2]. Esto se puede manifestar como una solución sostenible para la reducción de la dependencia energética de las fuentes fósiles, además de contribuir a que la industria del azúcar y el alcohol sea menos vulnerable a las variaciones en el desempeño del mercado [1]. Fito y col. [3] plantean que la biorrefinería de la caña de azúcar obliga a la integración de la destilería con el proceso azucarero y la caña como materia prima principal, lo que posibilita no sólo el empleo de las mieles finales, sino también de los jugos y mieles intermedias. En el presente trabajo se proponen alternativas que tienen como objetivo lograr un

aprovechamiento integral de corrientes derivadas del proceso azucarero e integrarlas a una industria azucarera como una biorrefinería de primera y segunda generación.

2 Desarrollo

El proceso inicial es la obtención de azúcar crudo a partir de la caña de azúcar y del cual se derivan las demás producciones. Considerar un esquema de segunda generación implica utilizar en mejor medida la biomasa lignocelulósica, en este caso bagazo, siendo no solamente para producir energía, sino para aprovechar su contenido de glucosa y xilosa. Por ello se propone para la obtención de etanol no emplear agua en la etapa de fermentación y usar la mezcla de sustratos azucarados formada por hidrolizado de bagazo, jugo de los filtros y miel, así como separar la xilosa contenida en la fibra de bagazo.

La obtención de etanol a partir de miel, jugo de los filtros e hidrolizado de bagazo consta de tres etapas fundamentales: pretratamiento, fermentación y destilación. La materia prima empleada es el bagazo sobrante de la fábrica de azúcar, del cual una parte considerable se utiliza como combustible en la generación de vapor. La incorporación de la etapa de hidrólisis enzimática en un central azucarero, con una planta de etanol tradicional, permitirá una reducción del consumo de miel por concepto de compra en tiempo de no zafra, incrementando capacidades de producción no aprovechadas, así como la adaptación de la industria azucarera como una biorrefinería integrada.

En la primera etapa de pretratamiento, para la obtención del hidrolizado de bagazo, se obtiene un líquido que contiene mayormente xilosa, glucosa y arabinosa. El mismo puede ser sometido a diferentes etapas de tratamiento para obtener una corriente con mayor contenido de xilosa que pueda constituir materia prima para la producción de xilitol. Los balances de materiales, para la obtención de una corriente rica en xilosa, se realizan a partir de la cantidad de líquido separado en la primera etapa del pretratamiento del bagazo. Por otra parte, en la elaboración de concentrados proteicos se pueden utilizar diferentes fuentes de sustratos. Para esta alternativa se considera la producción de levadura torula en crema utilizando *Cándida utilis* y las vinazas provenientes de la destilería como materia prima, de forma tal que se aproveche su contenido de materia orgánica y que una vez finalizado este proceso la vinaza residual se pueda emplear en la producción de biogás [4]. Esta es una alternativa que permite aprovechar las vinazas como fuente de sustratos azucarados, siendo una materia prima más económica que la miel final. De esa forma se evita el empleo de miel en el proceso, destinándola para la producción de etanol, y se obtiene una crema proteica que pueda ser aprovechada como alimento animal. Este proceso, además, ofrece una remoción de la DQO de un 40% aproximadamente, al disminuirla a 30000 mg/L, según los resultados de [5]. Con estos valores de carga orgánica se puede realizar la producción de biogás, mediante digestión anaerobia, disminuyendo el tiempo de retención en el biodigestor. Esto permite reducir en un 75% la carga orgánica contaminante, obtener lodo fertilizante y aguas residuales para ser utilizadas en el fertirriego. Este biogás producido puede ser empleado para la generación de vapor en la destilería, lo que representa un ahorro de combustible a emplear en la misma. Un resumen de lo antes expresado se manifiesta en la Figura 1, mientras que los resultados de los balances de materiales correspondientes a los principales productos se exponen en la Figura 2.

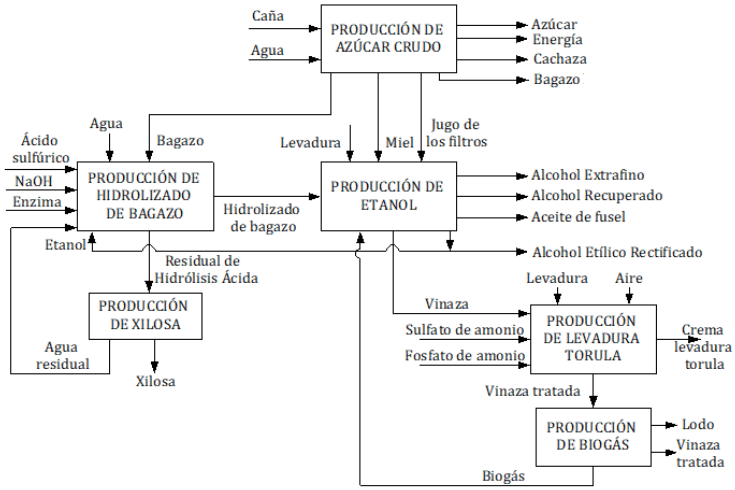

Figura 1. Esquema de biorrefinería propuesta.

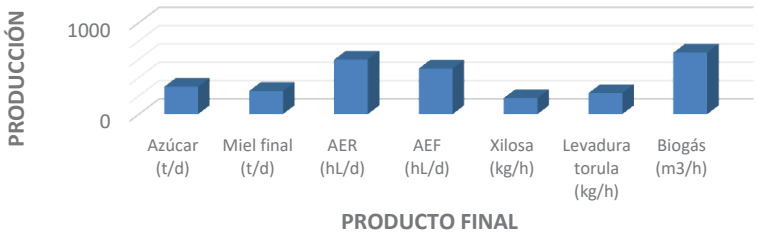

Figura 2. Principales resultados alcanzados a partir de los balances de masa.

El análisis económico se realiza aplicando la metodología planteada en [6], con el equipamiento necesario para cada proceso. Los costos totales de producción (CTP) se obtienen, entre otros aspectos, a partir de los consumos en materias primas, mano de obra y requerimientos. Mientras que, la ganancia se determinó en función del valor de la producción y del costo total de producción, para 300 días de operación al año (Figura 3). Con el objetivo de valorar la factibilidad de inversión del esquema de biorrefinería, se determinan los indicadores dinámicos de rentabilidad: VAN, TIR y PRD, tomando una tasa de interés del 15%. Inicialmente se realizan para cada proceso por separado. Los resultados se resumen en la Tabla 1. Como se puede observar, solo se logra rentabilidad en la producción de etanol como proceso independiente, sin embargo, cuando se analiza el complejo de forma integral como una biorrefinería, las ganancias que se alcanzan en la totalidad permiten la rentabilidad, con un período de recuperación de 5,5 años para 120 días de zafra. Con estos resultados se demuestra que la propuesta de esquema de biorrefinería es económicamente viable, considerando la producción azucarera establecida, realizándose extracción del jugo de los filtros y produciendo hidrolizado de bagazo con el bagazo sobrante.

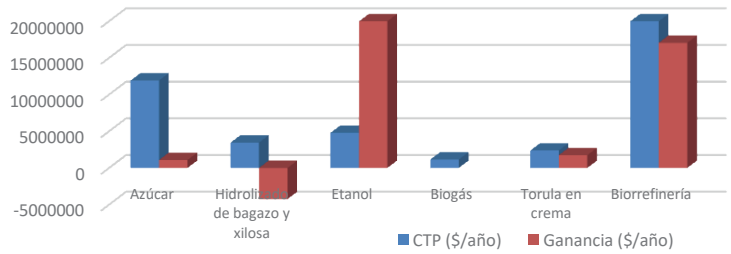

Figura 3. Costo total de producción y ganancia para cada tecnología analizada.

Tabla 1. Indicadores dinámicos de rentabilidad**.**

	Hidrolizado de Bagazo y xilosa	Etanol	Torula en crema	Biorrefinería
VAN ($)	-81 781 666	90 585 492	-14 297 833	48 389 965
TIR (%)	-	74	-	34,3

3 Conclusiones

La integración a una biorrefinería de segunda generación, que emplea el bagazo como materia prima lignocelulósica para obtener hidrolizado, unido al jugo de los filtros y la miel en la fermentación, reduce el consumo de esta última en un 24% y no necesita agua para realizar la dilución. Por otro lado, es posible obtener xilosa a partir del líquido residual del pretratamiento del bagazo por hidrólisis ácida, reduciendo el consumo de esta etapa en un 51 %.

La producción de levadura torula a partir de vinazas permite aumentar el valor agregado de este residual antes de ser usado en la producción de biogás. Desde el punto de vista económico, al analizar los procesos por separados, solo es factible la producción de etanol, pero el esquema general de biorrefinería resulta rentable para el período de zafra analizado.

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Modelado matemático de una planta piloto de producción de sidra para la toma de decisiones

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Resumen. En este trabajo se describe el desarrollo de un modelo matemático como herramienta de ayuda para la toma de decisiones durante el proceso de elaboración de sidra en una escala piloto de producción. El objetivo principal del modelo es optimizar la molienda de fruta respecto de los tanques de fermentación disponibles considerando satisfacer el volumen mensual de cada emprendedor que requiere el servicio. Dicha herramienta computacional proporciona condiciones operativas óptimas para definir un programa de producción mensual, pero además suministra información para elaborar diferentes escenarios a mediano y largo plazo que faciliten la planificación estratégica en la Planta Piloto de Alimentos Sociales (PPAS).

Palabras Claves. Modelado matemático - Programación mixto-entero lineal - Sidra - Optimización de la producción

1 Introducción

El Alto Valle de Río Negro y Neuquén, en la Patagonia Norte, es la principal área de producción de frutas de pepitas de Argentina. Esta región concentra aproximadamente el 85% de la producción de manzanas y el 75% de la producción de pera [1]. La producción de manzanas y peras alcanzó en el año 2017 aproximadamente un millón de toneladas, con una distribución prácticamente en partes iguales [2]. El 60% de la producción de manzana se destina al consumo en fresco mientras que el 40% restante se industrializa. De este último porcentaje destinado a la industria, aproximadamente el 70% se emplea en la producción de jugos concentrados, mientras que el 30% restante se destina principalmente a la producción de caldos de sidra [3].

Los altos niveles de calidad exigidos por los mercados internacionales derivaron en un incremento progresivo de los niveles de descarte de pera y manzana que alcanzan el 30 y 40%, respectivamente [4]. Este descarte es el que se emplea en la elaboración de sidra. En los últimos años, la fruticultura ha sufrido una constante crisis económica, lo cual sumado a los bajos precios pagados por la industria de transformación, obliga al sector a repensar sus estrategias para mejorar su rentabilidad.

El consumo mundial de sidra se duplicó en los últimos 10 años fundamentado sobre todo en la innovación de nuevos tipos de productos, similar a lo que ocurre con otras bebidas fermentadas como la cerveza, donde se observa una fuerte tendencia al desarrollo de productos distintivos [5]. Aún con este contexto internacional favorable, en Argentina la situación es diferente. En nuestro país se consumen aproximadamente 900.000 hL/año de sidra [6]. Sin embargo, el consumo ha descendido aproximadamente 6% por año en promedio durante los últimos 5 años, lo cual representa una pérdida de aproximadamente 20 millones de litros [7]. Por lo tanto, revalorizar el consumo nacional de sidra es importante desde varios puntos de vista.

En primer lugar, existe estacionalidad en el consumo, limitándose a una época específica, entre octubre y diciembre, donde se concentra aproximadamente el 80% del consumo anual. En segundo lugar, si bien gran parte de la industria sidrera se asienta en el Alto Valle, en la región sólo se elaboran los caldos que luego son enviados a Buenos Aires donde se fracciona y embotella el producto [6]. Por último, muchas de las sidras elaboradas industrialmente no cumplen con las regulaciones del Código Alimentario Argentino (CAA), pudiéndose deber a que se emplea el descarte de fruta para su producción [8]. Por lo tanto, es un desafío lograr elaborar productos con características distintivas que sean consumidos en cualquier época del año.

En los últimos años, además, se evidencia una marcada industria artesanal de la sidra llevada adelante por emprendedores, vinculados algunos con iniciativas de turismo rural. Este impulso ha sido dado por los nuevos emprendedores del sector donde cada uno normalmente procesa alrededor 200 - 300 kg de fruta de buena calidad. Muchos de estos emprendedores se orientan a la obtención de la sidra espumosa mediante la aplicación del método Champenoise [5].

Por otra parte, recientes investigaciones resaltan el potencial de cepas de levaduras nativas de *Saccharomyces uvarum* y *Saccharomyces eubayanus* como *starters* en la fermentación de mostos de manzana para la elaboración de sidras con calidad distintiva regional [5] [7]. Estas cepas muestran características distintivas como el contenido de glicerol y la baja producción de etanol con respecto a las cepas tradicionalmente empleadas en la elaboración como *S. cerevisiae* [5][7].

Con respecto al modelado durante las etapas de fermentación, se han propuesto modelos cinéticos para predecir la utilización de azúcares que permite anticipar medidas correctivas durante la fermentación de jugo de uva [9]. Además, se ha estudiado el efecto del contenido inicial de nitrógeno y la temperatura inicial de fermentación de jugo de manzana aplicando modelos basados en la cinética de Monod [10].

Teniendo en cuenta el contexto anterior, estudiar de manera integral el proceso completo de elaboración de sidras desde el lavado de la fruta hasta la obtención del producto terminado resulta de gran interés. El análisis del proceso permitirá optimizar las diferentes etapas de elaboración alcanzando una mejor rentabilidad del sector.

La simulación presenta una multiplicidad de ventajas para analizar un proceso productivo. Por ejemplo, las etapas de elaboración pueden ser analizadas disminuyendo el riesgo de inversiones de alto costo de implementación de equipos y procesos, permitiendo a la vez, evaluar modificaciones en cada una de las etapas de elaboración [11]. En la industria vitivinícola se han desarrollado plataformas de asistencia en la

toma de decisiones [12], mientras que para la producción de cerveza se aplicó optimización dinámica para el proceso de malteado [13].

En este sentido, el modelado matemático de procesos industriales se presenta como una alternativa interesante para el análisis global de una planta de elaboración de bebidas fermentadas. El desarrollo de herramientas computacionales que faciliten la asistencia en la toma de decisiones basadas en modelos matemáticos, permitirá optimizar la producción por medio del control de cada una de las variables que intervienen en el proceso de elaboración de sidras a partir de la fermentación del jugo de manzana y pera generando productos de mayor calidad, optimizar la utilización de recursos humanos y minimizar los costos de elaboración siendo esto la llave para tener productos competitivos a nivel nacional e internacional. Se han desarrollado modelos de simulación y optimización en la industria de jugos concentrados de manzana y pera destinados a mejorar la toma de decisión al momento de la elaboración de los diferentes productos [14]. Sin embargo, hasta el momento no se han encontrado en la literatura estudios sobre modelados matemáticos que optimicen la elaboración del proceso global de producción de sidras involucrando todas las etapas.

A nivel local, la PPAS perteneciente a la Universidad Nacional de Río Negro que se encuentra ubicada en la ciudad de Villa Regina, presenta múltiples objetivos y desafíos en la producción de sidra. Por un lado, permite el análisis y desarrollo de nuevas bebidas fermentadas de carácter regional y la obtención de subproductos intermedios para el desarrollo de otros productos como pueden ser los jugos, vinagres y destilados, todos a partir de diversas variedades de fruta de pepita a las que se tiene fácil acceso y de abundante producción en la zona del Alto Valle de Río Negro. Por otro, se pretende dar valor agregado a la producción frutícola de la provincia mediante la diversificación más allá de la producción primaria tradicional, buscando aprovechar los subproductos generados durante este proceso productivo para la elaboración de alimentos como fuente de fibra y antioxidantes, entre otros. En este sentido, la prestación de servicios a emprendedores de la región y el país, que pretendan optimizar su producción como así también mejorar o desarrollar productos nuevos, resulta de muchísimo interés. Por lo que es fundamental, el análisis del proceso productivo de manera global e integral a fin de evaluar la potencialidad de la planta piloto con el objetivo de cumplir las metas establecidas, donde el desarrolla de herramientas computacionales de apoyo para la toma de decisiones basadas en modelos matemáticos resultan fundamentales como soporte en las decisiones tácticas y operativas.

El objetivo de este trabajo fue desarrollar un modelo matemático de optimización del proceso de elaboración de sidras desde la recepción de la fruta hasta el embotellado y la obtención del producto terminado. Este modelo de optimización involucra un escenario de servicios solicitados por cuatro emprendedores en simultáneo durante el mes en análisis, por lo que es importante considerar el estado actual de ocupación de tanques de la planta piloto para ir habilitando las moliendas de cada emprendedor. De esta manera, el modelo de optimización permite obtener la planificación de producción en el horizonte de tiempo de 35 días en función de la capacidad de planta piloto y disponibilidad del personal.

2 Proceso de la Planta Piloto de Sidra

La planta piloto de elaboración de sidra (Figura 1) presenta las capacidades de producción que se detallan en la Tabla 1. Por otro lado, en la Tabla 2 se detallan los volúmenes de los 15 tanques que se disponen para la elaboración de sidra con su respectiva etapa de producción antes de comenzar a resolver el problema de optimización.

Tabla 1. Datos de la planta piloto de elaboración de sidra.

Capacidad de molienda (kg fruta/h)	400
Capacidad operativa (L)	1.950
Capacidad de llenado de botellas (botella 750 cm^3/h)	150

Tabla 2. Capacidad de almacenamiento y estado de ocupación en el día 1 del horizonte de planeamiento de cada uno de los tanques de la planta piloto.

Tanque	Capacidad [L]	Disponibilidad	Etapa
1	200	No	Ninguna
2	200	No	Ninguna
3	150	Si	Ninguna
4	150	Si	Ninguna
5	150	Si	Fermentación
6	150	Si	Ninguna
7	150	Si	Ninguna
8	50	Si	Clarificación
9	50	Si	Fermentación
10	400	Si	Clarificación
11	60	No	Ninguna
12	60	No	Ninguna
13	60	Si	Acondicionamiento
14	60	Si	Ninguna
15	60	Si	Ninguna

La Figura 1A muestra el equipamiento utilizada en la etapa física de la planta piloto de producción de sidra, mientras que la Figura 1B muestra los tanques de fermentación donde ocurre la etapa microbiológica así como también el equipamiento necesarios para la gasificación y embotella del producto. El proceso de producción de sidra se observa en la Figura 2, donde se detallan todas las etapas de elaboración desde el lavado de la fruta hasta el envasado de la sidra producida. Además, el diagrama de flujo muestra las salidas de productos de interés en las diferentes etapas del proceso.

La fruta seleccionada para ser procesada es volcada en una cuba lavadora donde se realiza un riguroso lavado, asegurando la correcta higiene del fruto. La fruta ya limpia es captada por un elevador a paletas que ingresa a una cinta de inspección donde se realiza el descarte de la fruta en mal estado. La fruta que avanza es transportada por

otro elevador a paletas que eleva la misma hasta la boca de ingreso a un molino triturador tipo martillo para ser triturada y convertirse en una pulpa homogénea. En el siguiente paso del proceso la pulpa ingresa a una prensa de bandas donde se obtiene el jugo, que es colocado en los diferentes tanques para realizar la fermentación donde se obtendrá el caldo de sidra. Para cada una de las etapas es posible utilizar un tanque con bomba para realizar los trasvases y recirculaciones, así como también un sistema de filtrado móvil.

El equipamiento se complementa con una saturadora con sistema isobárico de llenado, una tapadora diafragmática con sistema de vacío y una bozoladora para obtener un producto terminado en botella de vidrio [15].



Fig. 1. Equipamiento de etapa física (a) y etapa microbiológica con sistema de gasificación (b) de la planta piloto de sidra.

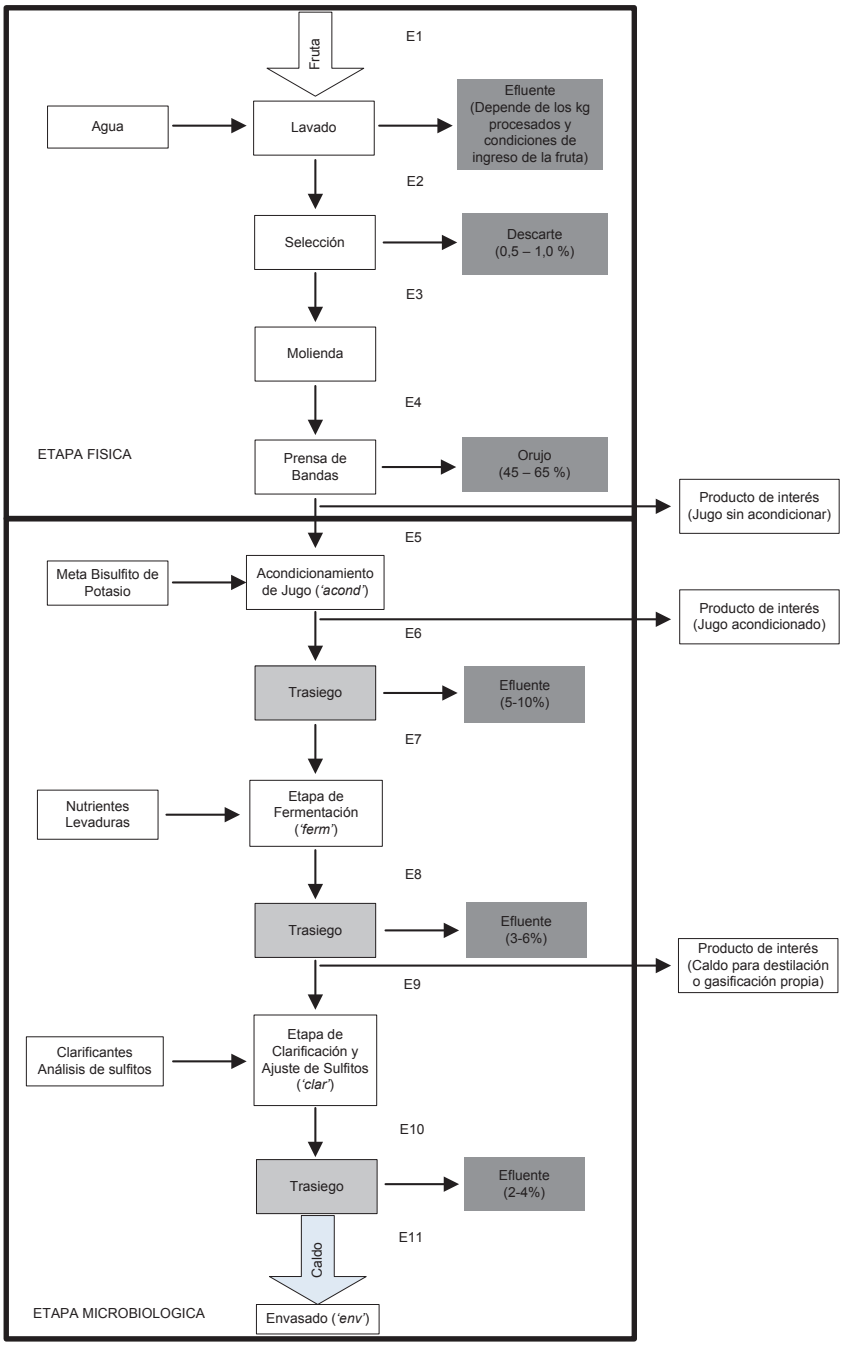

Fig. 2. Diagrama de flujo del proceso de producción de sidra y productos intermedios a escala piloto.

3 Modelo Matemático

En el modelo matemático desarrollado se presentan dos funciones objetivos que permiten abordar escenarios diferentes. La primera función objetivo (fobj=1), minimiza la cantidad de tanques utilizados durante el proceso de producción de sidra prefijando la cantidad de emprendedores y los litros de sidra que estén interesados en elaborar mensualmente. La segunda función objetivo (fobj=2), maximiza la productividad de la planta piloto de sidra en función de las restricciones operativas (tanto del equipamiento, cumplimiento del protocolo del COVID-19 y del personal disponible en la PPAS) que se detallarán más adelante.

Para el análisis, la elaboración de sidra se dividió en dos etapas: física y microbiológica. Cada etapa tiene un tiempo de duración mínimo y se incluye su correspondiente pérdida o descarte histórico de acuerdo con la Figura 2. Es importante destacar, que el modelo tiene la capacidad de considerar el estado actual de la planta al momento de la resolución del problema de optimización en ambas funciones objetivo. Es decir, se considera que tanques se encuentran ocupados, que volumen de jugo o caldo contienen, y por cuantos días en el horizonte de tiempo continuarán ocupadas según la etapa del proceso en la cual se encuentren.

Etapa Física: La etapa física involucra las etapas de lavado, selección de fruta y molienda. Se restringió la molienda a dos días a la semana, con el objetivo de representar una situación de trabajo real con el personal de planta disponible. Se consideró el ingreso de fruta a la etapa de lavado sólo los días, martes y jueves.
La molienda requerida por cada emprendedor debe realizarse una única vez en el horizonte, y se encuentra representada por la Ec. (1):

$$\sum_t y\_emp_{t,emp} = 1 \tag{1}$$

Donde, *emp* es un set que indica los emprendedores e $y\_emp_{t,emp}$ es una variable binaria que indica si el día *t* se está realizando la molienda del emprendedor *emp*. También se indica que sólo se puede procesar lo solicitado por un emprendedor cada día, a los fines de cumplir con los protocolos de COVID-19 establecidos en la PPAS como se muestra en la Ec. (2):

$$\sum_{emp} y\_emp_{t,emp} \leq 1 \tag{2}$$

Para todas las demás subetapas de las fases física y microbiológica, la entrada está dada por el siguiente balance de masa que muestra la Ec. (3):

$$E_{j,t} = E_{j-1,t} * (1 - perdida_{j-1}) \tag{3}$$

Donde *j* representa lavado, selección, molino y prensa de bandas en la etapa física y los trasiegos de la etapa microbiológica como se muestran en la Figura 2. El parámetro *t* representa la etapa en la que se encuentre del proceso.

Etapa microbiológica: Abarca el acondicionamiento del jugo (*'acond'*), fermentación (*'ferm'*), clarificación y corrección de sulfitos (*'clar'*) y envasado ('*env'*) como se muestra en la Figura 2. El ingreso a esta etapa de elaboración comienza con el jugo obtenido en la etapa física el cual será distribuido en los tanques disponibles, y luego será acondicionado para dar inicio a la etapa de fermentación mediante la utilización de una levadura comercial *Saccharomyces cerevisiae*. Además del aporte de jugo que viene de la etapa de acondicionamiento, es posible que al inicio del horizonte, algún tanque tuviese jugo en la etapa de acondicionamiento y, por ende, debiera ingresar a la etapa de fermentación dentro del horizonte, sin estar relacionado a una molienda programada. Por lo tanto, se deben tener en cuenta los dos aportes para el ingreso de caldo a la etapa de fermentación como indica la Ec. (4):

$$E_{6,t} = \sum_{tq} ent\_tq_{tq,t,'ferm'} + \left[\sum_{tq} cap\_tq_{tq} * y\_tq\_0_{tq,'acond'} * (1 - perdida_{acond})\right]_{si\ t=ocupado_{tq}+1} \quad (4)$$

Donde $ent\_tq_{tq,t,'ferm'}$ es una variable continua que representa el volumen que está ingresando al tanque *tq* el día *t* para la etapa de fermentación (*'ferm'*), cap_tq_{tq} es un parámetro que determina la capacidad del tanque *tq*, $y\_tq\_0_{tq,'acond'}$ es un parámetro que define si el tanque *tq* estaba ocupado originalmente para la etapa de acondicionamiento (*'acond'*) y $ocupado_{tq}$ es un parámetro que define la cantidad de días del horizonte que el tanque *tq* permanecerá ocupado. El +1 indica que al día siguiente se liberará y deberá ingresar a la etapa de fermentación. El mismo concepto se utilizó para modelar la etapa de clarificación (*'clar'*) y envasado/gasificación (*'env'*).

Una buena práctica de manufactura en el proceso de elaboración de sidra (y de bebidas fermentadas en general) es evitar que el tanque contenga demasiada cantidad de aire para que no repercuta negativamente en la etapa microbiológica. Por lo tanto, se debe asegurar que el contenido de líquido se mantenga por encima del 80% del volumen del tanque. A los fines de satisfacer este requerimiento operativo, se incluye la Ec. (5) como restricción:

$$ent\_tq_{tq,t,e} \geq cap\_tq_{tq} * 0.8 - 100 * cap\_tq_{tq} * (1 - y\_e\_tq_{tq,t,e}) \quad (5)$$

Donde, $y\_e\_tq_{tq,t,e}$ es una variable binaria que indica si el día *t* ingresó jugo al tanque *tq* para la etapa *e*. En este problema e representa las diferentes etapas: [*'acond', 'ferm', 'clar', 'env'*]. La variable binaria $y\_e\_tq_{tq,t,e}$ sólo se debe activar si está ingresando jugo al tanque *tq*, el día *t* para la etapa *e*. Para esto se deberán cumplir las siguientes restricciones que se muestran en las Ec. (6) y (7):

$$ent\_tq_{tq,t,e} \leq cap\_tq_{tq} * y\_e\_tq_{tq,t,e} \quad (6)$$

$$ent\_tq_{tq,t,e} \geq 10 * y\_e\_tq_{tq,t,e} \quad (7)$$

Para asegurar que un dado tanque asignado a una etapa del proceso de un dado emprendedor no pueda ser utilizado en simultáneo en otra operación, se incluyeron

restricciones como la que muestra a continuación para la etapa de fermentación ('*ferm*') Ec. (8):

$$y\_e\_tq_{tq,t,'ferm'} + \sum_{i=1}^{6} y\_e\_tq_{tq,t+i,e} \leq 1 \tag{8}$$

En cuanto a la función objetivo, la misma queda expresada como se muestra en la Ec. (9), donde si fobj=1 se minimiza la utilización de tanques de la planta y si fobj=2 se maximiza la producción siempre y cuando se maximice la variable OBJ:

$$OBJ = \begin{cases} -\sum_{t,tq,e} y\_tq_{tq,t,e} & si\ fobj = 1 \\ \sum_{t} E_{1,t} & si\ fobj = 2 \end{cases} \tag{9}$$

El modelo fue desarrollado en la plataforma de alto nivel para optimización matemática General Algebraic Modeling System (GAMS) y está constituido por un sistema de 55.235 ecuaciones y 9.976 variables. Con respecto a las ecuaciones, 425 son restricciones de igualdad y el resto restricciones de desigualdad. Relacionado con las variables, 2.661 son continuas mientras que el resto son variables binarias. La primera función objetivo se resuelve en 1,3 segundos y la segunda función objetivo en 0,5 segundos, ambas con un gap (diferencia entre la mejor posible solución entera y la mejor solución entera encontrada) igual a cero.

4 Discusión y Resultados

La Figura 3 muestra la ocupación global de tanques en la línea de producción (fobj=1) en un período de 35 días para la elaboración de sidra de cuatro emprendedores que procesan en promedio 515 kg mensuales. La resolución de este problema nos permite detectar la capacidad disponible en la planta piloto permitiendo incluir nuevos emprendedores para la elaboración de sidra o considerar aquellos usuarios que utilizan una parte de la línea de producción porque elaboran otros tipos de productos. Este es el caso de emprendedores que obtienen el jugo de manzana y elaboran en otros establecimientos diferentes productos, como por ejemplo vinagre, que para evitar contaminaciones no pueden llevarse a cabo en la PPAS o el caso de los que utilizan el caldo sin clarificar para realizar destilaciones con el fin de obtener calvados. Para este último caso es fundamental que las condiciones iniciales de la fruta que se utiliza sean óptimas, ya que en la etapa de destilación es crucial tener una buena recuperación de aromas para los productos que diseñan.

Sin embargo, cuando se resuelve el problema de maximización de la producción (fobj=2), se observa un aumento considerable de la ocupación de tanques en la planta piloto. Esto se traduciría directamente en un aumento sustancial de la cantidad de fruta procesada (aproximadamente se duplicaría el promedio mensual), repercutiendo en una mayor cantidad de producto terminado en el mismo horizonte de tiempo.

De esta manera, esta herramienta computacional permite maximizar el factor de utilización de la planta reduciendo costos mediante un mayor procesamiento de cantidad de fruta. Los resultados de la optimización no solo permiten aumentar la produc-

ción de cada emprendedor, sino que también ponen en evidencia que se alcanza el máximo de la capacidad de producción de 1.950 L en los días 14 y 16 del horizonte de planeamiento.

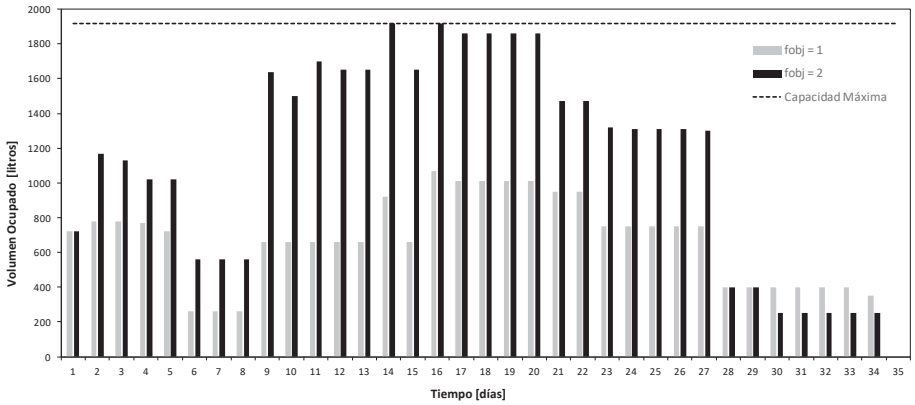

Fig. 3. Ocupación global de tanques en la línea de producción de sidra para las diferentes funciones objetivo (fobj=1 y fobj=2).

La Figura 4 muestra un diagrama de Gantt de los tiempos de elaboración de sidra para cuatro emprendedores que ingresan a elaborar sidra en ese período de tiempo a la planta, y donde se resuelve el problema utilizando la función objetivo que minimiza la utilización de tanques en la planta (fobj=1). La optimización del proceso permitiría disponer de un esquema de producción específico y diseñado para cada emprendedor evitando solapamiento de tanques durante el proceso de elaboración durante ese período de tiempo, donde además, esto queda sujeto a las restricciones operacionales y restricciones relacionadas con el cumplimiento de protocolo de COVID-19 detalladas en la sección anterior. Los resultados indican que se utilizarían solamente siete tanques de la planta piloto, donde se compartirían entre los emprendedores solamente los tanques 1 y 2 en la etapa física y los tanques 3, 4 y 5 en las etapas de fermentación y clarificación. Estos resultados tienen importantes implicancias prácticas, ya que este esquema le permitiría al emprendedor tener definido el tiempo a partir del cual tendría disponible el caldo para su posterior acondicionamiento y gasificación, permitiéndole establecer un esquema de compromisos de ventas de productos de manera precisa. Además, permitiría establecer una mejor coordinación con los nuevos lotes de producción evitando traer fruta a destiempo en la línea de elaboración lo que impacta negativamente en dos aspectos. Por un lado, se evitaría la sobremaduración de la fruta lo que puede significar una pérdida de la materia prima ocasionando además especificaciones que queden fuera de rango para obtener el producto deseado. Por otro lado, el aumento de costos por la utilización de las cámaras de frío para mantener la madurez de la fruta un tiempo determinado.

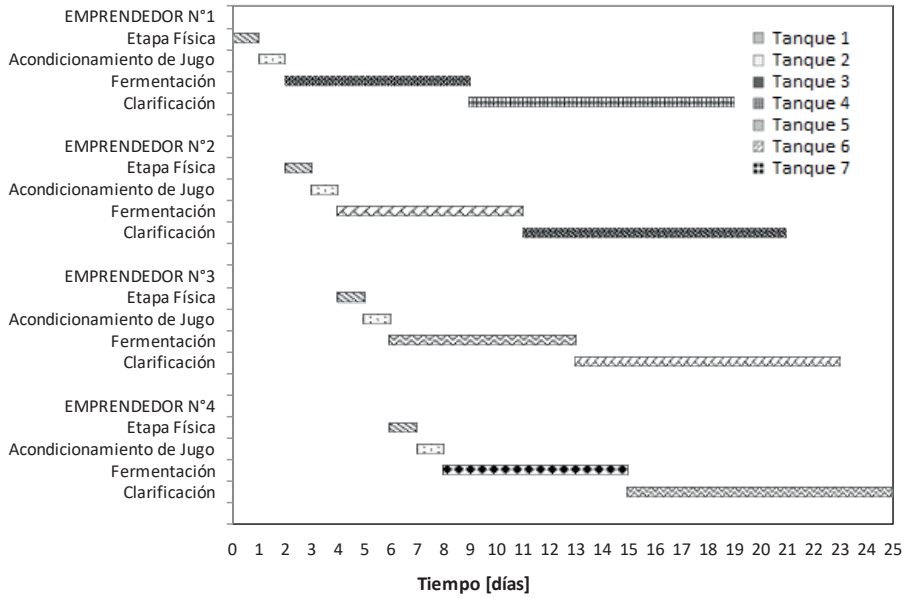

Fig. 4. Diagrama de Gantt para la producción de sidra para cuatro emprendedores.

5 Conclusiones

Las estrategias de simulación y optimización han sido habitualmente empleadas para investigar acerca de procesos y operaciones de muchos sectores de producción, tanto químicos como petroquímicos. Recientemente, la industria de alimentos comenzó a abrirse a este tipo de herramientas con el objetivo de optimizar sus procesos de producción. En este trabajo, se demuestra como la utilización de este tipo de herramientas computacionales brinda un soporte que permite sistematizar el proceso de toma de decisiones. Además, se desarrolló un modelo matemático de optimización de una planta piloto de elaboración de sidra. La herramienta desarrollada permitió organizar los esquemas de producción de la planta, disminuir o ajustar costos de producción, asegurándose de tener disponibilidad de equipos y personal para cumplir con los compromisos asumidos con los emprendedores que solicitan un servicio de elaboración de sidra.

A su vez, permitió visualizar el estado en el que se encuentra cada lote en cada día en el horizonte de planificación, permitiendo así, reducir las pérdidas de fruta en mal estado o sobremaduración durante la etapa de almacenamiento en la cámara de frío antes de ser procesada. Esto no es un aspecto menor, ya que los emprendedores destacan y diferencian sus productos con la adquisición de fruta de excelente calidad, pagando en muchos casos precios diferenciales con el objetivo de obtener las especificaciones que buscan para el desarrollo de sus productos.

El modo "maximizar producción" permitió encontrar un escenario donde se cumpla con todos los compromisos y a su vez permite aumentar la molienda para lograr una

mayor producción. Con esta función objetivo se puede calcular la producción máxima que se lograría en la planta con los equipos y personal disponible debido a las restricciones de personal que la pandemia del COVID-19 ha generado; así como también detectar cuellos de botellas en el proceso de elaboración.

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A Nonlinear Parameter Estimation for Biodiesel Production with *Nannochloropsis oceanica* CCALA 978

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Abstract. *Nannochloropsis oceanica* CCALA 978 is a promising native species for biodiesel and other value-added bioproducts. However, no models have been developed to predict lipid production in this microalga allowing production process improvement yet. A dynamic mathematical model was formulated for the optimization problem from different batch culture variables. Nitrogen and phosphorus limitation conditions of this strain were considered. The resulting optimization problem was formulated and based on orthogonal collocation methods as special class of implicit Runge-Kutta methods. The following nonlinear programming (NLP) problem was solved with an Interior Point method using AMPL (A Mathematical Programming Language) platform. Numerical results provide temporal profiles in good agreement with experimental data.

Keywords. Parameter Estimation – Simultaneous Dynamic Optimization – *Nannochloropsis oceanica* CCALA 978 – Biodiesel Production

1 Introduction

Microalgae have been widely proposed as a biomass resource for third and fourth generation of biofuels [1]. Oleaginous microalgae as some species of *Nannochloropsis* have been proposed as biodiesel source due to their robustness and growth capacity, high neutral lipid content (NL) and fatty acid quality [1]. Specifically, *Nannochloropsis oceanica* CCALA 978 is a native oleaginous strain which is characterized by accumulating neutral lipids up to 36% d.w [2], main raw material for biodiesel production. On the other hand, growth kinetic and physiological parameter modeling is an effective way to study the microalgal performance in terms of light distribution, nutrient uptake and temperature, among other variables [3]. Thus, mathematical modeling is presented as a powerful tool that allow analyzing the different

variables involved in microalgal culture for the optimization of biomass, lipids and other bioproducts production, and, at the same time, evaluating costs and profitability in obtaining biodiesel [3]. The main objective of this study was developing a dynamic model and fitting it using experimental data of biomass and chlorophyll *a*, phosphorus and nitrogen consumption and neutral lipid production in a batch culture of *N. oceanica* CCALA 978 under full nutrient conditions.

2 Experimental Data

Experimental data (data set) for parameter estimation problem and model developing were taken from Bongiovani [2]. For the parameter estimation problem, experimental data corresponding to first stage of cultivation batch (7 days of cultivation) under full conditions of nitrate (NO_3) and phosphate (PO_4) were used. Date set for the dynamic optimization problem were: biomass dry weight, dissolved nitrate, dissolved phosphate, neutral lipid accumulation and content of chlorophyll *a*.

3 Mathematical Model

The proposed model in the present work was based on the Packer [4] model for other microalgae species. Dynamic mass balances were formulated for main components of the system: biomass (equation 1), phosphate (equation 2), nitrate (equation 3), neutral lipids (equation 4), chlorophyll *a* (equation 5), growth rate (equation 6), temperature limitation (equation 7), photosynthesis maximum ratio (equation 8) and light collection (equation 9). The optimization problem for estimating parameters of the dynamic model is solved by minimizing the objective function (equation 10).

$$\frac{d[X]}{dt} = \mu * [X] - k_d * [X] \quad (1)$$

$$\frac{d[PO_4]}{dt} = -Y_{px} * \mu * [X] \quad (2)$$

$$\frac{d[NO_3]}{dt} = -Y_{nx} * \mu * [X] \quad (3)$$

$$\frac{d[L]}{dt} = p * [X] - CC * \mu * [X] \quad (4)$$

$$\frac{d[H]}{dt} = \frac{CC}{p} * \rho * \mu - \mu * [H] \quad (5)$$

$$\mu = \mu_{max} * fT \quad (6)$$

$$fT(Temp) = \left(\frac{Temp}{Topt}\right) * e^{[1-(Temp/Topt)]} \quad (7)$$

$$p = pm * [H] * \left(1 - e^{-I/Imax}\right) \quad (8)$$

$$I = I_0 * \left(1 - e^{-aa*[H]}\right) \quad (9)$$

$$\min \varphi = \sum_{i=1, j=Compound}^{N_D} \left(x_{estimated,j} - x_{experimental,j}\right)^2 \quad (10)$$

$$where\ j = [biomass, NO3, PO4, neutral\ lipids\ and\ chlorophyll\ a]$$

The objective function is subject to the differential-algebraic (DAE) systems described above and is minimized by manipulating the degrees of freedom presented in the Table 1.

Table 1: Estimated parameters results for the dynamic optimization problem.

Parameter	Meaning	Value	Unit
μ_{max}	*Maximum growth rate*	0.4987	[1/day]
k_d	*Mortality rate*	0.001	[1/day]
$Topt$	*Optimal temperature*	29	[°C]
Y_{px}	*Biomass phosphate yield*	3.604	[g PO_4/g Biomass]
Y_{nx}	*Biomass nitrogen yield*	0.149	[g NO_3/g Biomass]
CC	*Subsistence quota*	4.564	[g LN/g Biomass]
pm	*Maximum photosynthesis rate*	1.696	[m^3/(g chl . day)]
I_0	*Incident irradiance*	$1.051x10^5$	[mol photons/(m^2 . day)]
aa	*Optical cross section of chl factor * Light path factor*	0.0156	[m^3/g chl]

The NLP problem obtained from the orthogonal collocation over finite elements was addressed with AMPL [5] platform and coupled to the Interior Point method [6] which has been compiled with third parties dependencies under Windows operating systems. The correlation index (d) obtained, which is a standardized measure of the prediction error degree in the model, which it could be found between 0 and 1, was calculated [7].

4 Results and discussion

In Figure 1 (A-E), the kinetics of biomass, chlorophyll *a*, nitrate, phosphate and neutral lipids are presented. It is possible to note that profiles obtained were adequately fitted to experimental data values used in the parameter estimation problem.

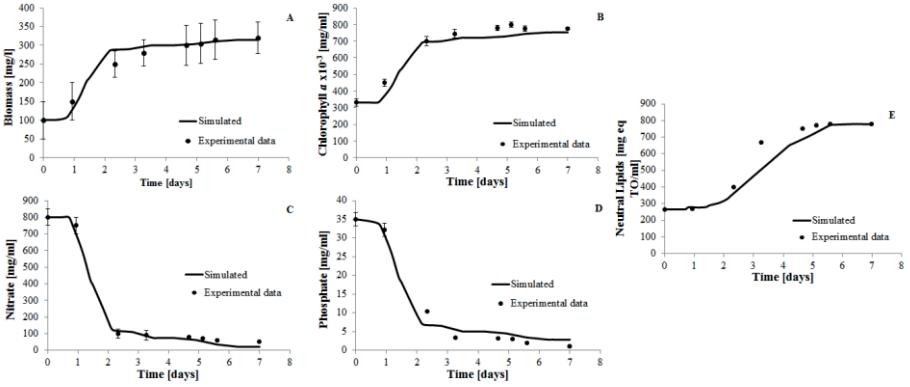

Figure 1: Experimental data and optimization results for biomass (A), chlorophyll *a* (B), dissolved nitrate (C), dissolved phosphate (D) and neutral lipids (E).

This was verified by statical index. This index demonstrated the good performance of model fitting with dimensionless values for correlation index (d) are closed to 1 (biomass: 0.9906; phosphate: 0.9874; nitrate: 0.9898; chlorophyll *a*: 0.9868; neutral lipids: 0.9751), indicating a good agreement between experimental data and obtained mathematical model profiles.

5 Conclusion

In this work, the mathematical model was a suitable tool for estimation of physiological parameters of *N. oceanica* CCALA 978.These results are promising for modeling a stage where functional inocula can be produced and then could be destined in a second induction phase for increasing neutral lipid concentrations under stress culture conditions. The mathematical model was calibrated with experimental data and it is a powerful tool to describe the physiological behavior in terms of biomass and neutral lipid production, nitrogen and phosphorus uptake in *Nannochloropsis oceanica* CCALA 978. This tool also allowing to obtain the behavior prediction and optimization of large-scale cultures for biodiesel production and other bioproducts with high added-value. Regarding computational cost, it was very small in time and iteration numbers for the IPOPT algorithm due to good initialization in primal and dual variables.

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Programación de Operaciones Eficiente de un Caso de Estudio Real de la Industria Farmacéutica mediante una Metodología de Descomposición Matemática-Algorítmica

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Resumen En este trabajo se presenta una metodología matemática-algorítmica para la programación de operaciones de instalaciones discontinuas multiproducto multietapa, desarrollada apuntando a resolver problemas de tamaño industrial. La propuesta se basa en la construcción iterativa de una solución mediante la resolución de una secuencia de subproblemas correspondientes a cada etapa, identificando y fijando las decisiones críticas en cada paso, y manteniendo información rigurosa de las cotas. La metodología se aplica a un caso de estudio real obteniendo soluciones de muy buena calidad en tiempos de cómputo competitivos.

Keywords: Plantas discontinuas multiproducto, Programación de operaciones, Optimización

1. Introducción

A pesar de innumerables esfuerzos en la formulación y solución de problemas de "scheduling" aún existe una importante brecha entre la teoría y la práctica, particularmente caracterizada por la dificultad intrínseca de resolver problemas de escala industrial. Harjunkoski y colab. [1] sostienen que las herramientas de optimización actuales pueden aplicarse satisfactoriamente para aumentar la eficiencia de la producción en piso de planta, aunque observan que existe mucho potencial de mejora. En este trabajo se presenta una metodología de programación de operaciones para plantas batch multiproducto multietapa considerando equipos en paralelo, almacenamiento ilimitado, y tiempos de transición dependientes de la secuencia, la cual es aplicada a un caso de estudio de escala industrial [2].

2. Metodología Matemática-Algorítmica Propuesta

La metodología propuesta consiste en un algoritmo iterativo que resuelve una secuencia de modelos matemáticos de tipo mixto entero lineal (MILP). Cada

uno de estos modelos corresponde a un subproblema del problema general, que considera una de las etapas y un subconjunto de las tareas previas y posteriores, requeridas en las etapas aguas arriba y aguas abajo del proceso. Para modelar los subproblemas se desarrolló una nueva versión del modelo de tiempo continuo basado en "ranuras" de tiempo de Pinto y Grossmann [3], en la cual es posible adicionar en un dado equipo una ranura o slot "comodín". Es decir, un slot multivaluado al cual puede asignarse un número arbitrario de lotes.

El algoritmo se estructura con una iteración principal y una iteración interna. La iteración principal, que considera todas las etapas del proceso, construye gradualmente una solución del problema completo fijando una a una las soluciones de cada etapa. En cada iteración principal, el conjunto de etapas pendientes (no fijadas) es analizado, resolviendo una secuencia de subproblemas (iteración interna) para cada etapa. Se busca así identificar la etapa crítica, es decir aquella que produce mayor deterioro al valor de la función objetivo (makespan). Una vez que esta etapa es identificada, las decisiones de asignación y secuenciación obtenidas en el subproblema correspondiente son fijadas, y el conjunto de etapas pendientes se reduce. La iteración principal finaliza cuando todas las etapas han sido fijadas y se obtiene una solución completa del problema (schedule).

La iteración interna, por su parte, se utiliza para resolver los subproblemas correspondientes a cada etapa. En esta iteración se resuelven, en forma alternada, un modelo aproximado y un modelo exacto. El subproblema aproximado se utiliza para obtener una configuración de ranuras candidata para la etapa, incorporando ranuras multivaluadas en todos los equipos. Posteriormente, el subproblema exacto fija la configuración de ranuras obtenida previamente para hallar una solución factible para la etapa. En base a la calidad de esta solución y los parámetros del algoritmo se decide terminar la iteración interna o repetir el proceso. En caso de continuar, la configuración de ranuras recientemente evaluada será descartada en los subproblemas aproximados siguientes mediante la incorporación de restricciones de tipo entero. La iteración interna retorna la mejor solución factible encontrada e informa en forma precisa las cotas (solución entera MIP y mejor solución posible) a la iteración principal.

Los parámetros considerados para la iteración interna en una etapa dada son los siguientes: (a) el número de ranuras R a considerar para los equipos de las etapas anteriores (aguas arriba) y posteriores (aguas abajo) del proceso, (b) un tiempo límite T para la resolución de cada subproblema, (c) un tiempo límite para la iteración interna, y (d) un número máximo de iteraciones admitidas. La terminación de la iteración interna ocurre luego de obtener una solución del subproblema exacto cuya mejor solución posible no puede mejorarse, o bien al excederse los límites fijados en (c) o (d).

3. Resultados y Discusión

El método propuesto fue aplicado a un caso de estudio real de la industria farmacéutica (ver [2]) que involucra una instalación "batch" multiproducto con 17 equipos operando en paralelo distribuidos en 6 etapas. Tomando como base el

problema de 30 baches, se evaluaron instancias incluyendo los primeros 10, 15, 20, 25 y 30 lotes. Se consideraron distintas alternativas para los parámetros (a) con valores R=2, R=3 y (b) con valores T=300, 600, 1200 s. Además, se fijó un tiempo máximo de 1 h y un límite de 10 repeticiones para la iteración interna.

La metodología fue implementada en GAMS, utilizándose el "solver" GUROBI 7.5 para la resolución de los subproblemas de la iteración interna. A fin de comparar el desempeño computacional y la calidad de la solución obtenida (valor de la función objetivo y cota de integralidad), se resolvieron además dos formulaciones completas del problema (es decir, considerando todas las etapas) fijando en este caso un tiempo límite de 5 h. Por un lado, se utilizó un modelo con un número de "slots" fijo equivalente a aquel de la mejor solución obtenida con la metodología propuesta (denominado FULL FIXED). Por otro lado, se resolvió un modelo que considera el número máximo de "slots" posible en cada equipo (FULL). Todas las evaluaciones computacionales se realizaron en un equipo PC genérico, con procesador Intel Core i7 3.2 GHz y 16 GB de RAM.

La Figura 1 muestra cómo al aumentar la cantidad de lotes la estrategia propuesta permitió obtener soluciones de mejor calidad y cotas inferiores similares a los problemas completos (FULL y FULL FIXED), a pesar de resolver únicamente subproblemas. Los tamaños de los modelos y tiempos de CPU para el problema de 30 lotes se comparan en la Tabla 1, donde se observa que la metodología propuesta considera problemas más pequeños, en particular con respecto al número de variables binarias. Finalmente, el diagrama de Gantt de la mejor solución obtenida para este problema se presenta en la Figura 2.

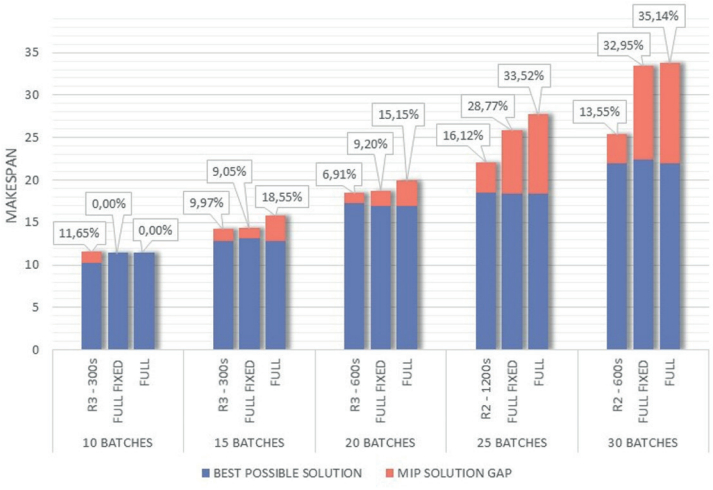

Figura 1: Comparación de las mejores soluciones obtenidas por la metodología propuesta con aquellas de modelos completos con número de ranuras fijo (FULL FIXED) o máximo (FULL).

Tabla 1: Comparación de tamaños de modelo y tiempos de CPU para 30 batches.

		Binary vars	Cont. Vars	Equations	Time (s)
R=2, T=600s	min	120	395	2935	5221
	max	1556	775	19583	
FULL FIXED		4090	775	19847	18000
FULL		10264	1384	50190	18000

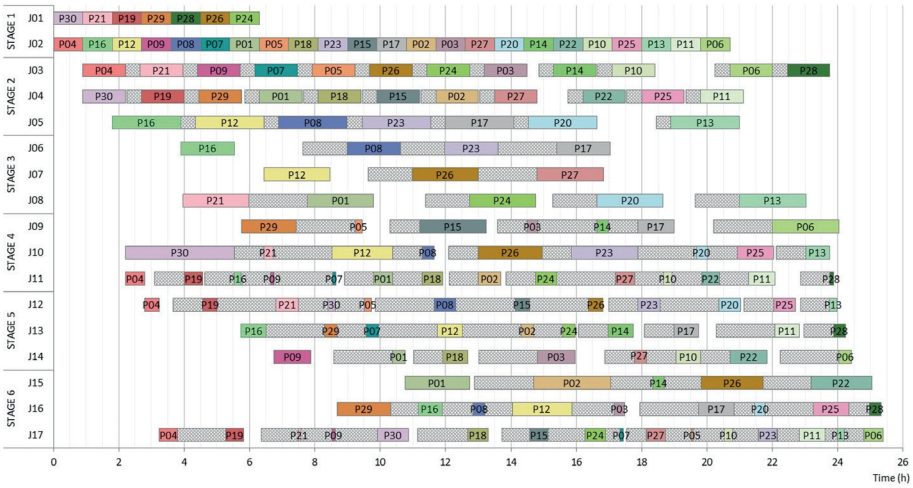

Figura 2: Diagrama de Gantt de la mejor solución obtenida (makespan: 25.38 h) para el problema de 30 lotes, con parámetros R=2 y T=600 s.

4. Conclusiones

Se presentó una metodología matemática-algorítmica basada en la resolución de una secuencia de subproblemas que permitió no sólo obtener soluciones de buena calidad en tiempos competitivos para problemas de escala industrial sino también proveer información rigurosa de las cotas de integralidad asociadas.

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Análisis de Incertidumbre en Modelos de Celdas de Combustible de Hidrógeno de tipo PEM

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Abstract. Las celdas de hidrógeno de membrana de electrolito polimérico son una prometedora fuente de energía limpia que, combinada con H_2 de origen renovable, presenta numerosas ventajas frente a la actual generación fósil. Dichas celdas convierten parte de la energía química de los reactivos (H_2 y O_2) en energía eléctrica, mientras que la otra parte se intercambia como calor. Una herramienta conveniente para calcular o estimar cuánta de la energía química se transfiere en cada una de estas formas es mediante la curva de polarización. En este trabajo se analizó la dispersión existente entre diversos modelos macroscópicos hallados en bibliografía para predecir la curva de polarización de este tipo de celdas de combustible. El objeto de este análisis fueron los modelos denominados 0-D. De estos fueron hallados y comparados 25, clasificables en 9 combinaciones según como son considerados los aportes del potencial electroquímico. De los resultados puede apreciarse cierta variación entre los diferentes autores. Existen ciertos comportamientos extremos, pero con una serie de modelos que siguen una tendencia central bastante similar. En esta primera etapa la dispersión fue analizada en función de la densidad de corriente donde se observa una elevada dispersión a altos valores de corriente y mínimos de dispersión en valores cercanos a (0,2-0,6 A/cm^2) donde suele operar este tipo de celdas. De todas maneras, lo recomendable es ajustar el modelo elegido a la celda con la que se desee trabajar.

Keywords: PEMFC, Modelado matemático, Análisis de dispersión.

1 Introducción

Las necesidades energéticas de la sociedad se han incrementado significativamente en los últimos años y las estimaciones proyectan que la tendencia seguirá en aumento, esperándose que para 2040 la demanda aumente entre 20% y 40% [1]. Actualmente la principal fuente de energía a nivel global es de origen fósil, causante de numerosos problemas ambientales y calentamiento global, además de ser no renovable. En este contexto, las fuentes renovables emergen como una posible solución para la generación de energía limpia. Una de ellas, foco de nuestro estudio, es la obtenida mediante celdas de combustible alimentadas por hidrógeno ya que poseen una gran eficiencia, no producen emisiones nocivas al ambiente y en los recientes años han tenido avances

significativos que permitirían la implementación comercial de estos equipos [2]. La celda tiene el propósito de convertir la energía química de los gases hidrógeno y oxígeno en energía eléctrica a través de una reacción electroquímica, generando una cantidad similar de energía que debe ser removida en forma de calor. Adicionalmente, si el gas hidrógeno utilizado se produce a partir de una fuente renovable el proceso se vuelve sostenible.

Una de las posibles formas renovables de obtención de hidrógeno para alimentar las celdas es a través del reformado de biomasa y posterior purificación de la corriente para eliminar el CO generado, que resulta un veneno para el electrocatalizador del ánodo. Dado que el proceso de reformado consume mucha energía resulta una buena práctica llevar a cabo una integración energética, consumiendo la menor cantidad posible de energía y aumentando el rendimiento energético global del sistema.

Desde la óptica del diseño del proceso, la pila de combustible es un reactor de flujo que tiene entradas y salidas de materia y energía, pero los simuladores comerciales de procesos no tienen dispositivos electroquímicos como operaciones unitarias, y sólo son capaces de informar la entalpía específica de reacción (Δh_{RQ}) y, mediante el caudal reaccionante, la entalpía total de reacción (ΔH_{RQ}). Según el Primer Principio de la Termodinámica para sistemas abiertos, se puede escribir para la celda:

$$\Delta H_{RQ} = P_{el} + Q_{int} \tag{1}$$

Dónde P_{el} es la potencia eléctrica y Q_{int} el calor generado intercambiado que debe ser removido. La potencia eléctrica es en definitiva lo que nos interesa producir, mientras que el calor es lo que nos interesa integrar. Por lo tanto, es requerida una herramienta externa que nos permita determinar los valores de P_{el} y Q_{int}. Dicha herramienta es la curva de polarización, que es la "huella digital" de un dispositivo electroquímico. El presente estudio discute diferentes modelos presentados en literatura, en particular los llamados 0-D.

Si bien existen diversos tipos de celdas de combustible, este estudio se enfoca en las celdas de membrana de electrolito polimérico (PEMFC). El "combustible" de la celda (H_2) es introducido en el ánodo, donde ocurre la oxidación al estado H^+ catalizada mediante platino, liberando electrones en el proceso. En el cátodo, se inyecta el agente oxidante (O_2) que se reduce captando los electrones liberados por el H_2. La reacción global que ocurre en la celda es:

$$H_2(g) + \frac{1}{2} O_2\ (g)\ \rightarrow H_2O\ (l) \tag{2}$$

En donde se forma agua liberando calor al medio. Usualmente este tipo de celdas operan en temperaturas alrededor de 60 a 90 °C.

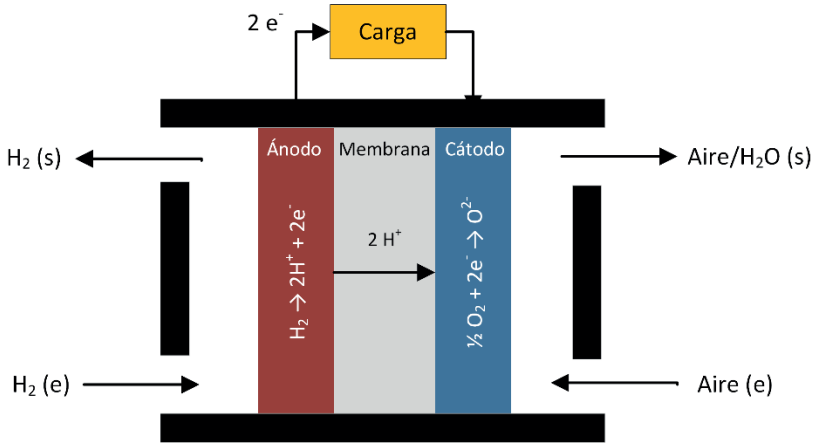

Fig. 1. Esquema de una celda de combustible de tipo PEM.

Es fundamental para el estudio de las celdas poseer un modelo que caracterice de la mejor manera posible el comportamiento de esta a través de su potencial electroquímico en función de la densidad de corriente circulante. Existe una gran cantidad de trabajos publicados [3-28] acerca de desarrollos de modelos para la curva de polarización.

El objetivo del presente trabajo es el de estudiar la dispersión existente entre los diversos modelos hallados en bibliografía con el fin de analizar el impacto de la selección del modelo (y de sus parámetros) en su capacidad para predecir la potencia, eficiencia y calor generado, variables fundamentales en la caracterización de una celda PEM.

2 Comparación de modelos de potencial de celda

El potencial de la celda (E_{tot}) puede modelizarse en función de 4 aportes distintivos:

$$E_{tot} = E_{nernst} - \eta_{act} - \eta_{ohm} - \eta_{conc} \tag{3}$$

Donde E_{nernst} es el potencial termodinámico (o de Nernst), y η_{act}, η_{ohm} y η_{conc} son, respectivamente, los sobrepotenciales de activación, óhmico y de concentración. A continuación, se describen estos aportes.

2.1 Contribuciones al potencial de la celda

Potencial de Nernst (E_{nernst}). Es el potencial reversible de la celda:

$$E_{nernst} = -\frac{\Delta g^{\theta}_{RQ}}{RT} + \frac{RT}{2F}\ln\left(p_{H_2}\, p_{O_2}^{1/2}\right) \tag{4}$$

Los modelos utilizan la expresión teórica arriba mencionada, cuya dependencia explícita con la temperatura absoluta (K) se muestra a continuación [3]:

$$E_{nernst} = 1{,}229 - 8{,}5.10^{-4}(T - 298{,}15) + 4{,}3085.10^{-5}\ \mathrm{T}\ \ln\left(p_{H2}.p_{O_2}^{1/2}\right) \quad (5)$$

Sobrepotencial de activación (η_{act}). Representa la energía que debe emplearse en la reacción electroquímica para apartarla del equilibrio de modo tal que pueda proceder y generar la circulación de electrones. Desde este punto de vista, la activación representa un gasto de energía que no podrá emplearse para realizar trabajo eléctrico sobre el medio. La descripción teórica de este fenómeno puede hacerse a partir de la ecuación de Tafel que permite estimar el sobrepotencial requerido en función de la densidad de corriente circulante (i):

$$\eta_{act} = a + b\log(i) \quad (6)$$

Los autores dan distintos ajustes numéricos para el cálculo de los valores de a y b en función de propiedades del sistema. Se muestran dos representaciones utilizadas:

Tabla 1. Modelos de potencial de activación.

Modelo	Ecuaciones	Fuente
Act 1(*)	$\xi_1 + T\left[\xi_2 + \xi_3 \ln\left(C_{O_2}\right) + \xi_4 \ln\left(i.A_{celda}\right)\right]$	[3]
Act 2(**)	$(\Delta V_0) + (\Delta V_a)\ .\ [1 - \exp\{-\chi_1\ i\}]$	[4]

(*) $\xi_2 = \xi_{2,0} + \xi_{2,1} \ln(A_{celda}) + \xi_{2,2} \ln\left(C_{H_2}\right)$

(**) $\Delta V_0 = \chi_{0,1} + \chi_{0,2}[\ln\left(p_{cat} - p_{sat,H_2O}\right) + \chi_{0,3}\ ]$; $\Delta V_a = \chi_{a,1}\left(\frac{p_{O_2,cat}}{0{,}1173} + p_{sat,H_2O}\right)^2 + \chi_{a,2}\left(\frac{p_{O_2,cat}}{0{,}1173} + p_{sat,H_2O}\right) + \chi_{a,3}$

Donde ξ y χ son parámetros ajustables del modelo. La relación entre la presión de los gases y las concentraciones en el líquido se realiza a través de la ecuación de Henry propuesta en [5]:

$$p_{O_2} = \left[5{,}08.10^6\ e^{-498/T}\right]C_{O_2} \quad (7)$$

$$p_{H_2} = \left[1{,}09.10^6\ e^{77/T}\right]C_{H_2} \quad (8)$$

Respecto de la presión de vapor del agua se utilizará el siguiente ajuste numérico [6]:

$$\log\left(p_{H_2O}\right) = -2{,}1794 + 0{,}02953\ T - 9{,}1837.10^{-5}T^2 + 1{,}4454.10^{-7}T^3 \quad (9)$$

Pérdida de potencial por resistencia óhmica (η_{ohm}). Se divide en dos aportes. Por un lado, la circulación de iones a través de la membrana (R_M) y, por el otro, la resistencia de contacto entre la membrana y los electrodos (R_C) que está relacionada con la circulación de electrones.

$$\eta_{ohm} = (R_C + R_M)\ i\ A_{celda} \quad (10)$$

La resistencia a la conducción de electrones se suele asumir independiente de los parámetros operativos de la celda [7], lo que varía entre los autores es la forma de estimar la resistencia a la conducción de protones. Esta se modela como un conductor:

$$R_M = r_M \frac{l_M}{A_{celda}} \tag{11}$$

La resistencia específica de la membrana r_M tiene un origen empírico y se muestran a continuación algunas expresiones halladas en bibliografía.

Tabla 2. Modelos de la resistividad de membrana (r_m).

Modelos	Ecuaciones	Fuente
Ohm 1	$\frac{181{,}6[1 + 0{,}03\, i + 0{,}062\, (T/303)^2\, i^{2{,}5}]}{[\lambda - 0{,}634 - 3\, i]\, \exp\{4{,}18(1 - 303/T)\}}$	[7]
Ohm 2	$[\alpha_1 T + \alpha_2\, i\, A_{celda}](l_M/A_{celda})$	[8]
Ohm 3	$\frac{1}{[\epsilon_1\, \lambda - \epsilon_2]\, \exp\{\epsilon_3(1/303 - 1/T)\}}$	[6]

Donde α y ε son parámetros ajustables del modelo. Adicionalmente el espesor de la membrana (l_M) y el contenido de agua de la membrana (λ) se toman como constantes en el modelado de la membrana.

Pérdida de potencial por concentración (η_{conc}). Su importancia se incrementa cuando la velocidad de consumo de los reactivos es elevada (altas densidades de corriente) lo que lleva a establecer perfiles de concentración más pronunciados en la celda. Existe una densidad de corriente máxima (i_{max}) en donde la velocidad de consumo de reactivo por la celda está dada por la máxima capacidad de difusión en la fase gaseosa.

Tabla 3. Modelos de potencial de concentración.

Modelos	Ecuaciones	Fuente
Con 1	$-b \ln (i/i_{max})$	[9]
Con 2	$a \exp\{b\, i\}$	[10]
Con 3	$\zeta_1 (i/i_{max})^{\zeta_2}$	[4]

Siendo a, b y ζ parámetros del modelo. En la tabla 4 se muestran 9 clases de modelos en base a como los diversos autores combinan las tres caídas de potencial que experimenta la celda.

3 Análisis de incertidumbre

Los diversos modelos de celda hallados en bibliografía fueron estudiados para analizar la dispersión existente en su capacidad de predecir el comportamiento de la celda frente a las variables operativas con el fin de proveer herramientas útiles en la selección de un modelo que permita caracterizar las celdas de hidrógeno. Los parámetros

sobre los que se practicará este análisis son la eficiencia de la celda (ε_{celda}), la potencia eléctrica generada (P_{gen}), cuyas expresiones son:

$$\varepsilon_{celda} = E_{tot}/\left(\Delta h_{RQ}/2F\right) \tag{12}$$

$$P_{gen} = E_{tot}\ (i\ A_{celda}) \tag{13}$$

Tabla 4. Combinaciones de modelos de celda electrolítica de tipo PEM.

Modelo	Activación	Ohm	Concentración	Fuentes
1	Act 1	Ohm 1	-	[5], [7], [11], [12]
2	Act 1	Ohm 2	-	[3], [8], [13]
3	Act 1	Ohm 3	-	[14]
4	Act 1	Ohm 1	Con 1	[9], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]
5	Act 1	Ohm 1	Con 3	[25]
6	Act 2	Ohm 2	Con 2	[10], [26]
7	Act 1	Ohm 2	Con 1	[27]
8	Act 1	Ohm 3	Con 1	[28]
9	Act 2	Ohm 3	Con 1	[4]

También serán tenidos en cuenta el calor intercambiado (ecuación (1)) y el potencial electroquímico de la celda (ecuación (3)). Para realizar este estudio se mantuvieron constantes los diversos parámetros físicos y operativos de la celda (A_{celda}, T_{celda}, p_{H2}, p_{O2}, λ y l_M) cuyos valores son informados en la Tabla 5. A continuación, se muestran los gráficos de las variables de estudio:

Tabla 5. Parámetros de celda utilizados en el análisis de dispersión.

Parámetro	Valor
Área (A_{celda})	50 cm^2
Temperatura (T_{celda})	85 °C
Presión H_2 en ánodo (p_{H2})	3 atm
Presión O_2 en cátodo (p_{O2})	2 atm
Contenido de agua en membrana (λ)	23
Espesor de membrana (l_M)	178 µm

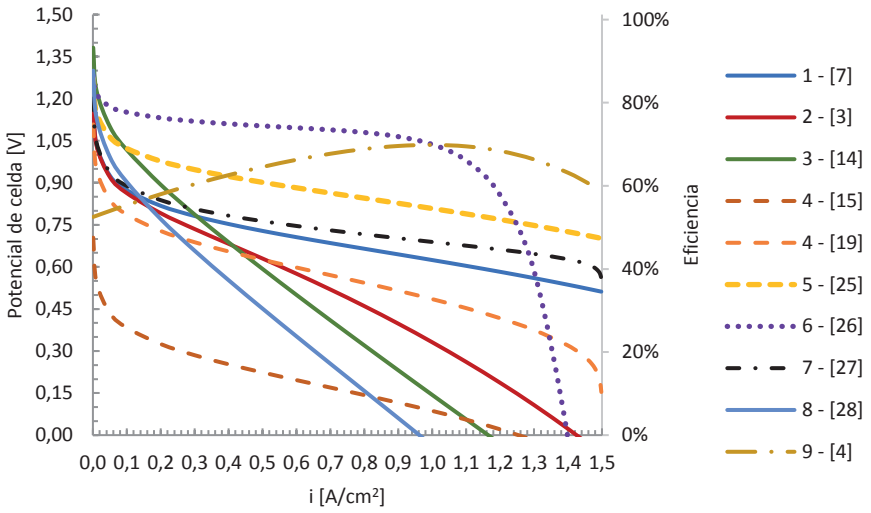

Fig. 2. Comparación de la predicción de la eficiencia y potencial de la celda PEM en función de la densidad de corriente para distintos tipos de modelo.

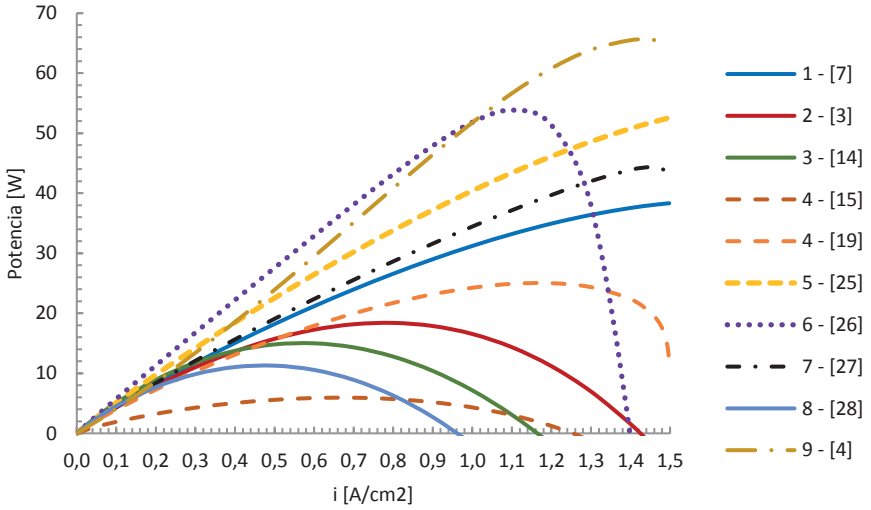

Fig. 3. Comparación de la predicción de la potencia generada por la celda PEM en función de la densidad de corriente para distintos tipos de modelo.

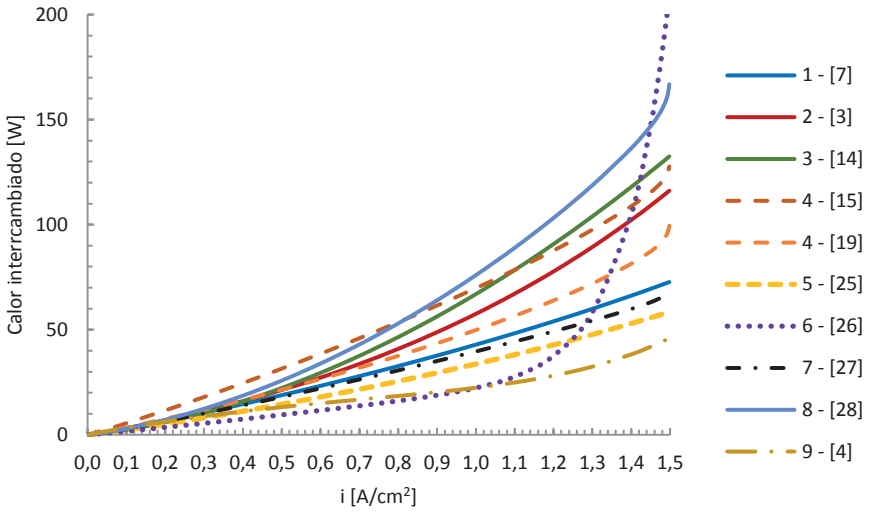

Fig. 4. Comparación de la predicción del calor generado en la celda PEM en función de la densidad de corriente para distintos tipos de modelo.

Los datos se muestran agrupados por combinación de modelo y luego por autor. Considerando que la eficiencia y el potencial de la celda tienen la misma forma ya que están relacionados por la constante ($\Delta h_{RQ}/2F$), se decidió mostrar ambas variables en el mismo gráfico. También cabe destacar que se muestran solo algunos de los modelos analizados, representativos de todas las combinaciones, quedando los restantes comprendidos entre el 4-[19] y el 5-[25] en las tres figuras. Como puede apreciarse, existe cierta similitud para la potencia y eficiencia a pequeños valores de densidad de corriente y, luego, existe una mayor dispersión a altos valores. Dado que a altas densidades de corriente el paso limitante es el de transferencia de materia, es de esperar que los parámetros de transporte (i.e. los coeficientes de difusión) sean posibles fuentes de dispersión entre modelos. A su vez, la resistencia específica r_M depende también de los parámetros de transporte, con lo cual su efecto se propaga también aquí y hace que la dispersión se manifieste antes de alcanzarse la zona de control por transporte de masa, a altas densidades de corriente. Respecto del calor generado hay una mayor concordancia para todas las densidades de corriente.

De todas maneras, con el fin de estudiar con mayor profundidad las diferencias existentes entre los modelos, se optó por graficar el coeficiente de variación (o dispersión relativa) (CV) que es representado como el desvío estándar (σ) sobre el valor medio (μ):

$$CV = \sigma/\mu \tag{14}$$

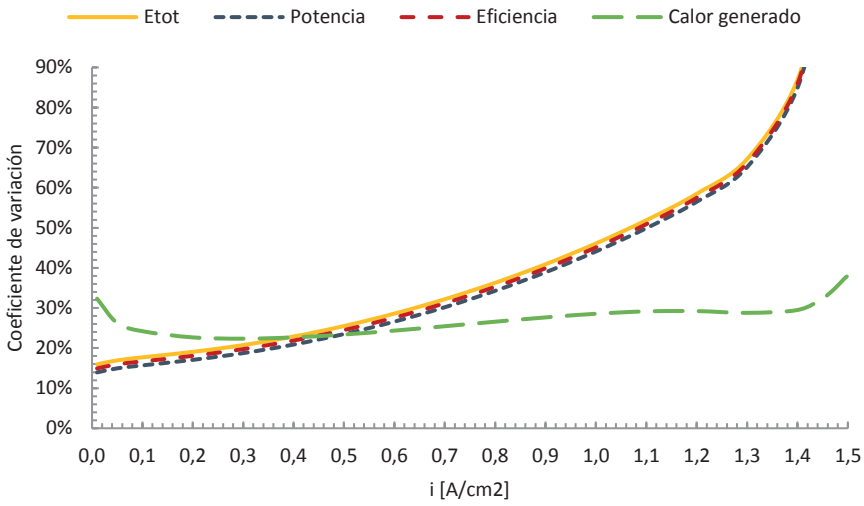

Fig. 5. Dispersión relativa de los modelos en la predicción del potencial electroquímico, potencia, eficiencia y calor generado de la celda PEM.

A bajas densidades de corriente se aprecia una pequeña dispersión relativa para las cuatro variables. Cabe destacar que el potencial total, potencia y eficiencia poseen la misma dispersión relativa ya que los tres se encuentran relacionados por constantes a una dada densidad de corriente (ecuaciones (12) y (13)):

$$E_{tot} = \left(\frac{1}{i\ A_{celda}}\right) P_{el} = \left(\frac{\Delta h_{RQ}}{2F}\right) \varepsilon_{celda} \tag{15}$$

A medida que aumenta la densidad de corriente la dispersión se hace mayor, aunque de manera menos significativa para el calor generado que para los otros tres parámetros.

4 Conclusiones

En este trabajo fueron testeados 25 modelos de celdas de hidrógeno de tipo PEM con el objetivo de analizar la dispersión existente entre ellos y entender el impacto que tendría la selección de cada uno en las distintas variables de la celda como la potencia generada, la eficiencia y el calor liberado.

En base a los tres términos que se deben representar del potencial de la celda (activación, ohm y concentración) estos 25 modelos pueden ser clasificados en 9 combinaciones distintas.

Del análisis realizado se puede observar que la dispersión relativa entre los modelos es pequeña para bajas densidades de corriente y luego aumenta con la densidad de corriente, aunque en el caso del calor generado esta variación es pequeña debido a una suerte de compensación que existe entre el incremento de la potencia y, a su vez, el

consumo de hidrógeno en la celda. De esto se podría suponer que la fuente de dispersión está en los parámetros de transporte ya que las mayores diferencias ocurren en la zona dominada por este fenómeno.

Por tanto, se concluye que la dispersión entre los modelos no es tal como para afectar significativamente los cálculos en una simulación en el rango en el que suelen operar las celdas de combustible tipo PEM (0,2-0,6 A/cm^2), aunque fuera de este rango se vuelven importantes las desviaciones halladas. Siempre será lo ideal ajustar datos empíricos de una celda en particular que sea la de interés en la aplicación ingenieril con el objetivo de minimizar el error de los parámetros operativos de la celda.

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Robust data reconciliation applied to steady state model with uncertainty

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Abstract. Different researchers have proposed the treatment of uncertainties in measurements because they interfere in the process state estimation. Data reconciliation procedure improves the information supplied by measurements, minimizing the discrepancy existent between measurements and accurate process model. This problem allows obtaining unbiased estimation when measurements follow exactly a normal distribution. Nevertheless, the presence of outliers do not allow the use of the former procedure, therefore Robust Data Reconciliation is developed. This latter provides accurate solutions when measurements follow approximately the normal distribution. Although many advances have been developed to treat measurement uncertainties in Data Reconciliation framework, there are not research works that consider model and measurement uncertainties simultaneously in presence of outliers. In this work, a Simple robust Method, which takes advantage of temporal redundancy, is applied to benchmarks that contain uncertain parameters. Performances measures are tested for different magnitudes of simulated outliers and compared with the ones provided by a classic Data Reconciliation procedure. Results show that the Robust Data Reconciliation procedure can yield unbiased estimations of measurements and parameters when outliers and parametric uncertainties are present.

Keywords: Robust Data Reconciliation, Model uncertainty, Measurement uncertainty, Parameter estimation, Outliers.

1 Introduction

Uncertainties in measurements are given by random events which always are present and produce fluctuations in the observation provided by instruments. These errors can be dealt with procedures as Data Reconciliation (DR). It's well known that DR gives accurate estimations when the assumptions of normality and model accuracy are true. Nevertheless, the presence of systematic errors in measurements or uncertainty in models is a common scenario in an industrial process. Therefore, both should be taken into account for the study of process state.

Systematic errors, as outliers, deteriorate the assumed distribution. Thus, different tests or techniques to detect and eliminate outliers before executing a DR procedure have been proposed [1]. Using Robust Data Reconciliation (RDR) stands out from the

former methodologies since it is able to mitigate the effect of outliers without using auxiliary methodologies [2, 3].

Researchers have proved RDR effectiveness in different operational conditions [2, 3]. This procedure uses M-estimators as objective function instead of the Least Square (LS) function. M-estimators are a generalization of the Maximum Likelihood function and can be classified as monotone or redescending according to their first derivative, which is called Influence Function (IF) [4].

In real-time operation, multiple sources of uncertainties deteriorate the model. This consideration allows avoiding the use of inappropriate models which leads to incorrect state estimation [5]. Some examples are ignored changes of physical flows state, chemical reactions conditions which change kinetics parameters; inaccuracies in model parameters related to energy balances and changes in the process state.

There are few proposals to deal with parametric uncertainty in models using DR. In this sense, [6] and [7] treated linear model which contain error measurements that follow the normal distribution ($\mathcal{N}$). The former research was a semi-empirical technique which used an iterative procedure to weight each constraint regarding to its uncertainties, while the latter research presented two modified DR procedures. Both DR problems provided identical estimations of parameter uncertainties, however the second highlighted because this allowed computing the variables estimation that satisfies the updated model. Furthermore, the latter authors discussed the concepts of redundancy and observability and showed that both diminish when the model contains uncertain parameters. Vasebi et al. [8] demonstrated the importance of selecting uncertainty covariance matrices to treat bilinear system. The three aforementioned research works did not take into account outliers. Recently, the presence of outliers was addressed at the development of a decision support tool when stochastic uncertainty in the demand exists [9]. Although the uncertainty studied was not parametric, this work remarks the importance of obtaining accurate estimation as a first step in the chain of an economic optimization problem.

The papers reviewed show the usefulness of RDR for a posterior step of optimization. This allows proposing the following hypothesis: RDR can treat model with uncertainty when outliers are present. To verify the hypothesis, this research work uses two linear benchmarks which contain parameter uncertainties. A RDR procedure is devised which uses a Simple Method (SiM) developed by [2] to get unbiased estimations of measurements and parameters for two models of error propagation. First, three case studies are presented which compare the results of SiM with the ones obtained by a classic DR problem using a model extracted from [7]. Different magnitudes of outliers are simulated and results of Performance Measure (PM) are presented in performance curves. Finally, a second model is treated with two methodologies which take advantage of temporal redundancy.

This research work is organized as follows. Section two briefly describes the RDR strategy executed for the estimation of measurements and uncertain parameters. Section 3 presents the measurement models considered and Performance Measures (PM) selected to inform the improvement attained. The results in terms of PM for two linear benchmarks are presented in Section 4. Finally, section 5 presents the conclusions achieved.

2 Methodology

Data reconciliation is an optimization problem which uses as objective function the LS. This procedure takes advantage of the spatial redundancy provided by the model equation to minimize the discrepancy between measurements and restrictions. [10]

In general, the solution of DR is a vector of estimated measured, $\hat{\mathbf{x}}^{LS}$, and unmeasured variables, $\hat{\mathbf{u}}^{LS}$, that strictly satisfy the model.

$$
\begin{aligned}
[\hat{\mathbf{x}}^{LS}, \hat{\mathbf{u}}^{LS}] = \underset{\mathbf{x},\mathbf{u}}{Min} & \left(\mathbf{y}-\mathbf{x}\right)^T \boldsymbol{\Sigma}^{-1} \left(\mathbf{y}-\mathbf{x}\right) \\
st. \quad & \\
& \mathbf{f}(\mathbf{x},\mathbf{u})=\mathbf{0} \\
& \mathbf{h}(\mathbf{x},\mathbf{u}) \le \mathbf{0} \\
& \mathbf{x}^{\mathrm{L}} \le \mathbf{x} \le \mathbf{x}^{\mathrm{U}} \\
& \mathbf{u}^{\mathrm{L}} \le \mathbf{u} \le \mathbf{u}^{\mathrm{U}}
\end{aligned}
\qquad (1)
$$

where $\boldsymbol{\Sigma}$ represents the covariance matrix, while $\mathbf{y}$ stands for the vector of random measurements. Furthermore, $\mathbf{f}$ and $\mathbf{h}$ stand for equality and inequality constraints, respectively. The upper and lower bounds of the optimization variables are represented with the suffix U and L respectively.

Narasimhan et al. (2012) treated parameter uncertainties solving the problem 2:

$$
\begin{aligned}
[\hat{\mathbf{x}}^{LS}, \hat{\boldsymbol{\theta}}] = \underset{\mathbf{x},\boldsymbol{\theta}}{Min} & \left(\mathbf{y}-\mathbf{x}\right)^T \boldsymbol{\Sigma}^{-1} \left(\mathbf{y}-\mathbf{x}\right) + \sum_p \left(\frac{\theta_p - \hat{\theta}_p}{\sigma_{\theta,p}} \right) \\
st. \quad & \\
& \mathbf{A}_\theta \mathbf{x}=\mathbf{0}
\end{aligned}
\qquad (2)
$$

where $\hat{\mathbf{x}}^{LS}$ and $\hat{\boldsymbol{\theta}}$ represent the state and parameter reconciled vectors and $\mathbf{A}_\theta$ the model with uncertain parameters [7]. This formulation considers that all the variables are measured. However, if there are unmeasured variables, procedures as QR factorization can provide a reduced problem which includes measured variables [10].

Problem (2) allows address model with uncertainty but does not consider that outliers may exist. Such errors invalidate the assumption of normality, thus the use of classic DR is not suitable. Conversely, Robust Data Reconciliation (RDR) yield unbiased estimation not only when measurements follow exactly the $\mathcal{N}$, but also when they do approximately [4]. Regards uncertain parameters, the presence of outliers can corrupt their estimation, therefore a RDR seems to be a promising strategy to get unbiased estimations of measurements and parameters.

2.1 M-estimators

M-estimator of location, $\hat{x}$, of the *i*-th variable is the solution provided by the following minimization problem:

$$\sum_{i=1}^{n} \rho\left(y_i - \hat{x}\right) = Min! \tag{3}$$

where ρ symbolizes the robust estimator. Based on this function the mathematical expressions of the IF (ψ) and Weight functions (W) are developed.

$$\sum_{i=1}^{n} \psi\left(y_i - \hat{x}\right) = 0 \tag{4}$$

$$\sum_{i=1}^{n} W_i \left(y_i - \hat{x}\right)\left(y_i - \hat{x}\right) = 0 \tag{5}$$

where $\psi = d\rho(x)/dx$ and W is defined in terms of ψ [4].

According to their IF, M-estimators are classified as monotone or redescending. The former are convex functions, therefore they always converge to the optimal solution. The latter W tend or are equal to zero, because of that redescending estimators are more efficient for heavy-tailed data. However, they require a good starting point to ensure attaining the global solution. Examples of monotone functions are the Huber (HU) and Fair functions, while classical redescendig estimators are the Biweight (BW) and Hampel functions [11]. Taking into account the former analysis, researchers proposed a Simple Method (SiM) which takes advantage of the M-estimators characteristics. [2]

2.2 Simple Method

Different strategies have been developed to solve the RDR problem, a comparison among their performances established that SiM can be applied for the measurement treatment in real-time optimization loops because it provides a good balance between the estimation accuracy and the computational load. The SiM comprises two sequential steps, which are the following:

Step 1: A robust median $\tilde{y}_i$ of the i-th variable, (i= 1: I), is calculated using a moving window of measurements, which length is N, and the BW function.

$$\tilde{y}_i = Min \sum_{p=j-N+1}^{j} \rho_{BW}\left(\frac{y_{ip} - \tilde{y}_i}{\sigma_i}\right) \tag{6}$$

where σ_i stands for the measurement standard deviation and j represents the actual time.

Equation (6) takes advantage of the temporal redundancy supplied by a window of observations and eliminates the outlier effect because BW is a redescending function. This problem is initialized with the solution of the j-1 time for j>1 or the mean of a data moving window if j=1.

The BW function is defined as follows:

$$\rho_{BW} = \begin{cases} 1-\left[1-(a/c_{BW})^2\right]^3 & if \quad |a| \le c_{BW} \\ 1 & if \quad |a| > c_{BW} \end{cases} \qquad (7)$$

$$a = \left(\frac{y_{ip} - \tilde{y}_i}{\sigma_i} \right)$$

where c_{BW} stands for the tuning constant calculated to fix the asymptotic efficiency of the BW estimator.

Step 2: The state of the system at the time interval j, $\hat{\mathbf{x}}_j^R$, is obtained by solving the following optimization problem

$$[\hat{\mathbf{x}}_j^R] = \underset{\mathbf{x_j},\mathbf{u_j}}{Min} \quad \sum_{i=1}^{I} \rho_{HU}\left(\frac{\tilde{y}_i - x_i}{\sigma_i} \right) \qquad (8)$$

$$st.$$

$$\mathbf{Ax=0}$$

where ρ_{HU} and a corresponds to:

$$\rho_{HU} = \begin{cases} a^2 & if \quad |a| \le c_{HU} \\ 2c_{HU}|a| - {c_{HU}}^2 & if \quad |a| > c_{HU} \end{cases} \qquad (9$$

$$a = \left(\frac{\tilde{y}_i - x_i}{\sigma_i} \right)$$

where c_{HU} is the tuning parameter of the HU function and a stands for the standardized measurement error. The solution achieved is optimal, because this step applies a monotone estimator. The computation time of the RDR is reduced initializing the problem with a good starting point that is the robust median obtained in Step 1.

2.3 RDR with uncertainty parameters

Fluctuations around a state or variations of operative conditions generate uncertain models since they affect the model equations. In this first approach, the parametric uncertainty is tackled.

The following development is based on a maximum likelihood procedure which assumes independence between measurements and model with uncertain parameters, which are distributed following $\mathcal{N}(0,\ \sigma^2_{\theta,p})$ [6].

A RDR problem is formulated which allows obtaining the measurement and parameter estimations for process operating in steady-state. Equation (10) presents the RDR problem formulated at the j-th time:

$$\left[\hat{\boldsymbol{x}}_j^{\,R}, \hat{\boldsymbol{\theta}}_j\right] = \underset{\mathbf{x_j}, \boldsymbol{\theta}_\mathbf{j}}{Min} \quad \sum_{i=1}^{I} \rho_{Hu}\left(\frac{\tilde{y}_i^R - x_i}{\sigma_i}\right) + \sum_{p=1}^{P}\left(\frac{\theta_p - \hat{\theta}_p}{\sigma_{\theta,p}}\right)^2$$

$$s.t. \qquad \mathbf{g}(\mathbf{x}, \boldsymbol{\theta}) = 0 \tag{10}$$

where $\hat{\boldsymbol{x}}_j^R$ and $\hat{\boldsymbol{\theta}}_j$ stand for the reconciled measurements and parameter vectors, respectively, $\mathbf{g}(\mathbf{x}, \boldsymbol{\theta})$ represents the model with p, p=1:P, uncertain parameters.

The problem (10) uses as initial point the robust median presented in Eq.6. The major differences between the problem devised in this work and [6] are the use of a robust estimator to mitigate the presence of outliers and the temporal redundancy that is taken into account at the robust median computation. It is expected that this formulation allows achieving accurate estimations independently of the lack of redundancy of some variables.[12]

3 Implementation

The RDR problem of (Eq. 10) is implemented for two measurement models which include measurements that follow the $\mathcal{N}$ and measurements which contain outliers.

3.1 Measurements Models

Random errors. They are caused by unknown and unpredictable fluctuations which may occur in the measuring instruments or in the operational conditions. These errors generate inconsistencies between the measurements and the process model.
The measurement model at the *j*-th time of the *i*-th variable, y_{ij}, is the following:

$$y_{ij} = x_i + e_{ij} \tag{11}$$

where x_i stands for the true value of the variable and e_{ij} represents the random error.
Outliers. These are extreme values deviated from the bulk of observation. A low probability (p_G) of outliers occurrence is defined since they are presented with a lower frequency than random errors. The outlier model equation is:

$$y_{ij} = x_i + e_{ij} + K\sigma_i \tag{12}$$

where *K* stands for the magnitude of the outlier.

3.2 Performance Measures

Mean Square Error (MSE) and Root (RMSE). These PMs are related to the variance and bias achieved with the estimated values. Such parameters can be computed globally and individually for each variable as follows:

$$MSE = \frac{1}{I\ J}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(\frac{\hat{x}_{ij}-x_i}{\sigma_i}\right)^2 \tag{13}$$

$$RMSE_{\rho,i} = \sqrt{\frac{1}{J}\sum_{j=1}^{J}\left(\frac{\hat{x}_{ij}-x_i}{\sigma_i}\right)^2} \qquad \rho = LS, RDR \tag{14}$$

where $\hat{x}$ stands for the estimated value and J stands for the number of trials simulation.
Ratios. Different ratios are evaluated and compared to analyze the improvement or deterioration achieved with the DR procedure. The root mean square error ($RMSE_y$) of measurements is calculated as follows:

$$RMSE_{y,i} = \frac{1}{J}\sum_{j=1}^{J}\left(\frac{y_{ij}-x_i}{\sigma_i}\right)^2 \tag{15}$$

Ratios are calculated as follows:

$$R_{\rho,i} = \frac{RMSE_{\rho,i}}{RMSE_{y,i}} \tag{16}$$

Spatial Redundancy (SR). This PM is computed following the procedure presented by Maronna and Arcas (2010).

$$SR_i = 1 - h_i \tag{17}$$

where h_i is the i-th diagonal element of the hat matrix **H**. This matrix allows calculating the reconciled variable values as a linear transformation of the measurements. It is defined in terms of the matrix that represents the process model and the measurement covariance matrix [13].
Parameter mean ($\tilde{\theta}_p$) and standard deviation (std ($\hat{\theta}_p$)). Both are calculated for each parameter using the estimations of J trials.

$$\tilde{\theta}_p = \frac{\sum_{j=1}^{J}(\hat{\theta}_{p,j})}{J} \qquad p = 1:P \tag{18}$$

$$std(\hat{\theta}_p) = \sum_{j=1}^{J} \left(\frac{\hat{\theta}_{pj} - \tilde{\theta}_p}{J} \right) \qquad p = 1:P \tag{19}$$

3.3 Useful consideration for the RDR implementation

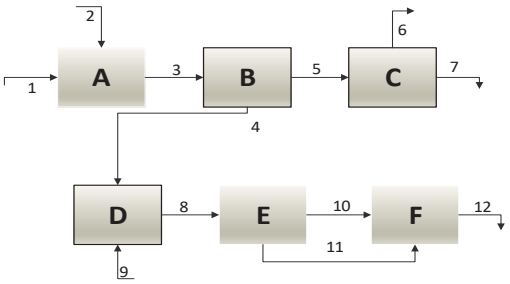
- A matrix of measurements of size [I x J] is generated to treat the same set of data for all the simulations of a benchmark.
- The global probability of outliers is fixed on p_G=0.1
- Outliers magnitudes are simulated on the range [0:10]
- Linear models are transformed into nonlinear because of uncertainty
- Equation (16) is used for computing the *SR* of variables of nonlinear models. Such models have been previously linearized

4 Results

Two linear benchmarks are treated with the proposed technique. The first one is extracted from [7]. Its PMs obtained with SiM and the procedure used in [7] are compared at different scenarios. The second model compares the DR solution when temporal redundancy is considered.

4.1 Model 1

This linear model comprises 12 measured variables, which are interconnected by six balance equations. Three balances include uncertain parameters, these are highlighted in Figure 1. The values of variables and parameters considered in [7] are reported in Tables 1 and 2.



$$F_1 + F_2 - F_3 = 0;$$
$$F_3 - F_4 - p_1 F_5 = 0;$$
$$F_5 - F_6 - p_2 F_7 = 0;$$
$$F_4 - p_3 F_8 + p_4 F_9 = 0;$$
$$F_8 - F_{10} - F_{11} = 0;$$
$$F_{10} + F_{11} - F_{12} = 0;$$

Fig. 1. Model 1 with 4 uncertain parameters

Table 1. Flows true values

I	1	2	3	4	5	6	7	8	9	10	11	12
F	70	30	100	60	40	20	20	91	31	44	47	91
σ_i	3.5	1.5	4.9	3.0	0.4	0.15	0.1	1.7	1.5	1.05	0.5	1.65

Three cases of study are proposed. Case 1 tests an accurate model. Case 2 estimates the uncertain parameters using as initial point the values informed by [7]. Finally, Case 3 formulates a model that fixes the uncertainty in the values reported at [7]. This case is analyzed to show the deterioration estimation when uncertainties exist but are not considered. Results of PMs are reported in Tables 3, 4, 5 and Figures 2, 3 and 4.

Table 3 present the SR and Ratios (R) for all the variables of the first model. The comparison of SR between Cases 1 and 2 shows that the lowest values of SR are obtained for Case 2, thus estimations accuracy diminishes. This fact represents an increment of RMSE for the model with uncertainty.

Table 2. Parameters and standard deviation values

θ_p	p_1	p_2	p_3	p_4
Value	1.8651	2.3325	0.7493	1.4603
$\sigma_{\theta,p}$	2	0.8	2	1.6

Table 3. *SR* and *Ratios* for random measurements

	Case 1			Case 2			Case 3	
F	$SR_{i,1}$	$R_{LS,1}$	$R_{SiM,1}$	$SR_{i,2}$	$R_{LS,2}$	$R_{SiM,2}$	$R_{LS,3}$	$R_{SiM,3}$
1	*0.7402*	0.5184	0.1606	*0.3181*	0.8267	0.2644	7.9353	13.7292
2	*0.1359*	0.9197	0.2857	*0.0584*	0.9653	0.3007	3.5026	0.3077
3	*0.9252*	0.2737	0.0885	*0.6235*	0.6077	0.1972	6.6046	9.6614
4	*0.8022*	0.4368	0.1412	*0.0000*	1.0000	0.3332	11.5925	12.1756
5	*0.8316*	0.4137	0.1327	*0.0000*	1.0000	0.3293	44.1636	66.6664
6	*0.1183*	0.9345	0.2981	*0.0000*	1.0000	0.3241	17.5425	0.3214
7	*0.0526*	0.9788	0.3104	*0.0000*	1.0000	0.3174	27.3919	0.3077
8	*0.7838*	0.4739	0.1533	*0.7618*	0.4964	0.1636	0.4994	0.1624
9	*0.3018*	0.8294	0.2722	*0.0000*	1.0000	0.3254	1.0368	0.3017
10	*0.4386*	0.7562	0.2467	*0.4003*	0.7790	0.2565	0.7825	0.2554
11	*0.0995*	0.9391	0.3032	*0.0908*	0.9448	0.3065	0.9452	0.3061
12	*0.7705*	0.4888	0.1581	*0.7472*	0.5119	0.1687	0.5150	0.1675

Ratios are computed as the division between $RMSE_{LS}$ or $RMSE_{SiM}$ in relation to $RMSE_y$. Ratios below 1 mean that the estimation procedure achieves more accurate results than measurements. Let analyze the PMs of variable F_4 at Case 2. Its redundancy is $SR_{4,2}=0$, while its ratios are $R_{LS,2}=1$ and $R_{SiM,2}=0.33$, $R_{SiM,2}<R_{LS,2}$. These results show that LS is not able to enhance estimation, however SiM allows correcting the measurements. This is due to the fact that SIM uses temporal redundancy. A general ratios comparison shows:

- LS: the R of Cases 1, 2 and 3 confirm that uncertainty deteriorates the accuracy of the estimation procedure. Estimation of Case 2 provides better results than

raw measurements, but non-redundant variables (*SR*=0) are not corrected. This is in concordance with theory. Case 3 presents the worst results, therefore not treating the uncertainty is not a smart decision.

- SiM: this procedure shows similar tendency than the obtained for LS. However, for Cases 1 and 2, the most accurate results are attained with SiM. The use of *SR* and temporal redundancy allows achieving more accurate results for redundant and non-redundant variables.

In Case 3 there is not a clear tendency between the ratios of SiM and LS, however this is a limit case since both estimation procedures present high deterioration.

The *MSE* of the measurements (*y*) and the three cases studied are reported in Table 4. A rough comparison lets arrive at similar conclusions than the ones obtained with R of Table 3. However, Case 3 shows that the highest deviation is reached with SiM.

The ability to mitigate the presence of outliers and get accurate parameter estimations are analyzed for Case 2. Results are presented in Table 5, and Figures 2, 3 and 4. The *MSE* results demonstrate that the most accurate results are attained with SiM for all the *K* considered. Least Square estimations are deteriorated whit the increment of *K*, while the robust procedure does not present significant changes.

Table 4. MSE of cases studied for random measurements

	Case 1		Case2		Case 3	
y	LS	SiM	LS	SiM	LS	SiM
0.9913	0.4955	0.0508	0.7463	0.0785	271.6773	405.7392

Table 5. MSE for different outlier magnitudes

K	0	2	4	6	8	10
y	0.9913	2.4091	5.0099	9.6123	16.9779	27.9915
SiM	0.0785	0.1058	0.1192	0.0909	0.0885	0.0912
LS	0.7463	1.0628	1.9339	3.4379	5.5103	8.2281

The selection of four variables with different let analyze this PM influence, these are F_2, F_5, F_8 and F_{10}. Their RMSE curves are presented in Fig. 2. Figures 2.a and 2.b stand for variables non-redundant (F_5) and with low redundancy (F_2), while Fig. 2.c and 2.d represent variables with *SR* equal to 0.40 (F10) and 0.76 (F_8). As it was expected, it is observed that LS achieves better results when *SR* increase, however this estimator is not able to enhance the estimation of non-redundant variables. On the other hand, SiM results show that all the variables can give accurate results independently of their *SR*.

Figures 3 and 4 present the means and standard deviations (stds) estimated with the LS and SiM for different outlier magnitudes.

- LS: The first parameter (p_1) presents the highest deviation, while the lowest is obtained for p_4. The stds of the first parameter p1 takes values between [0.1073-0.3415] and p_4:[0.0166-0.0545]

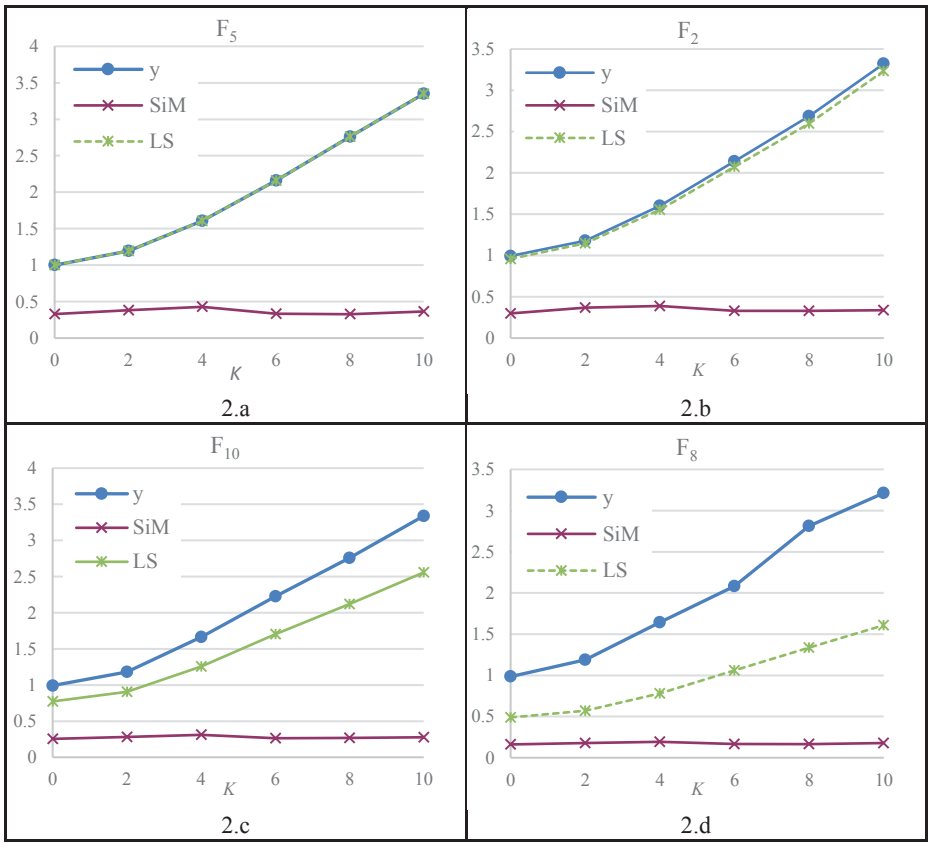


Fig. 2. Curves of RMSE for variables with different *SR*.

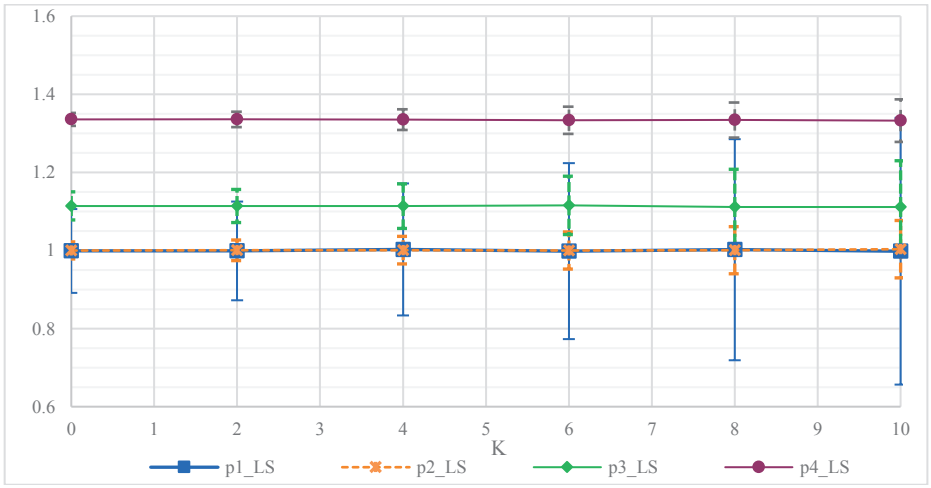


Fig. 3. Parameters' mean and standard deviation estimated using LS

- SiM: Similar to LS, the std of p_1 and p_4 present the highest and lowest std($\tilde{\theta}_p$). However, these parameters take values between [0.0351-0.0431] and [0.0054-0.0065] respectively.

A comparison of both methods shows that the means calculated for SiM and LS are similar, nevertheless the stds computed with LS are bigger than the ones corresponding to SiM. This tendency is observed for all the *K* tested.

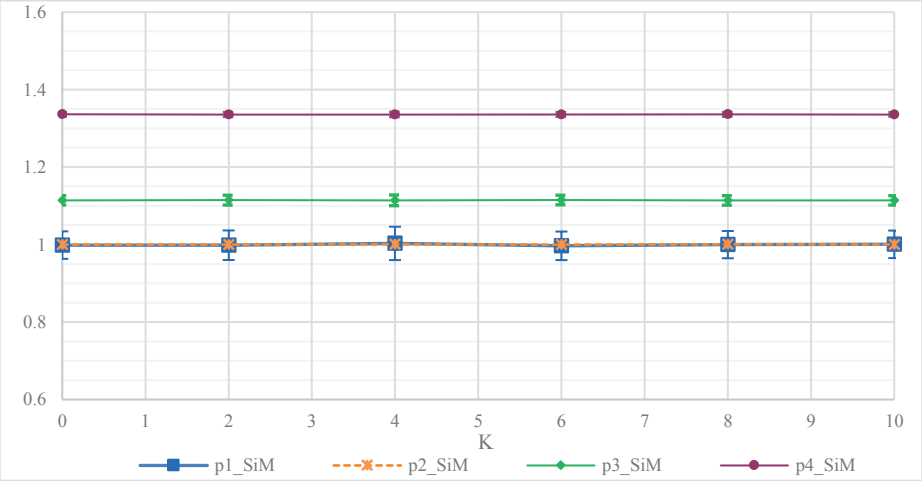


Fig. 4. Parameters' mean and standard deviation estimated using SiM

4.2 Model 2

This case of study allows compares the behavior of M-estimators and LS function when temporal redundancy is taken into account. The classic DR problem is initialized with the mean of a measurement data window that is called LSw.

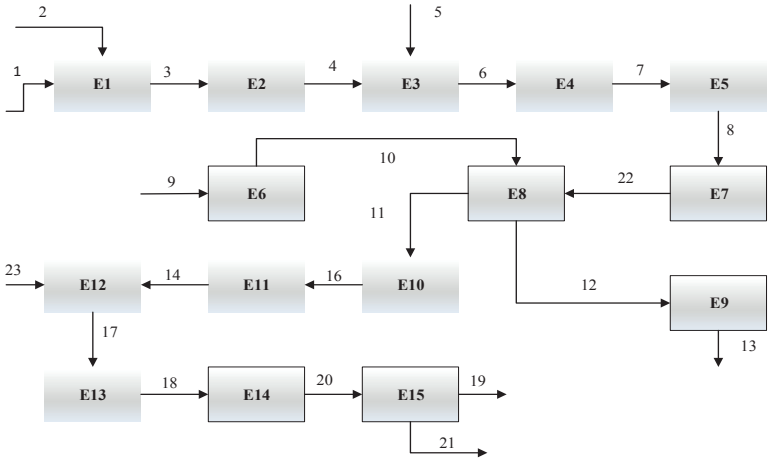


Fig. 5. Model 2 with uncertainty

Model 2 is a linear model composed of 23 flows related by 15 process units. The 6 units highlighted in Fig. 5 are the ones which have uncertain parameters, their initial values are presented in Table 6. Differently to Model 1, Table 7 presents the suggested values for parameters and standard deviation. These are improved by solving the DR or RDR problem for K=0. Then, the upgraded parameters are fixed as initial values for the following simulations. Results are displayed in Table 8, Figures 5 and 6.

Table 6. Balances Equation with uncertainty

$F_9 p_1 - F_{10} p_2 = 0;$	$F_{12} p_3 - F_{13} p_4 = 0$
$F_8 - p_6 F_{22} = 0;$	$F_{18} - F_{20} p_5 = 0;$
$F_{10} p_2 + F_{22} p_6 - F_{12} p_3 - F_{11} = 0;$	$F_{20} p_5 - F_{19} - F_{21} = 0;$

Table 7. Initial values of parameters and std

$\hat{\theta}_p$	p1	p2	p3	p4	p5	p6
Value	1,8	1,5	2	1,8	1,5	1,2
$\sigma_{\theta,p}$	2	0,8	2	1,6	2	0,8

Table 8. MSE for different K

K	0	2	4	6	8	10
y	0.9991	2.3946	4.9611	9.5848	16.9928	27.8381
SiM	0.0639	0.0865	0.0932	0.0738	0.0716	0.0711
LSw	0.0620	0.0865	0.1505	0.2720	0.4342	0.6162

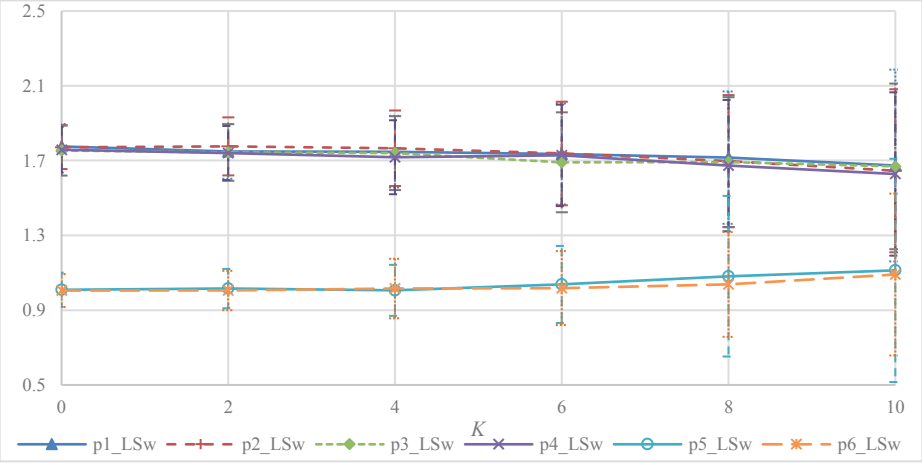


Fig. 5. Water Network parameter means and std of LSw

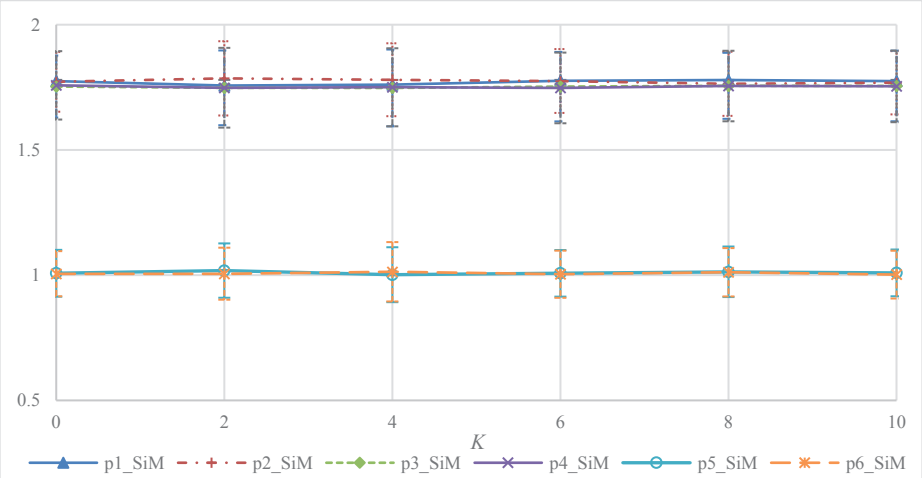


Fig. 6. Water Network parameter means and std of SiM

Table 8 shows that both procedures achieve more accurate results than the ones provided by the measurements. The LSw presents the most accurate estimation for $K \leq 2$ for $K>2$ the MSE increases until reaching the maximum value for $K=10$. The deterioration is smaller than the observed in the first example, this is as a result of the use of temporal redundancy. The SiM gets similar MSE for all the range of K analyzed.

Figures 5 and 6 display the means and stds of uncertain parameters. The lowest stds are achieved by LSw when measurements follow the $\mathcal{N}(K=0)$. However, this PM deteriorates with the increment of K, achieving stds that are 3 or 6 times bigger than the ones corresponding to SiM for $K=10$.

In conclusion, Figure 5 shows that the stds of all the parameters get worse with the increment of K, therefore the means of the parameters also deteriorate. Opposite, Figure 6 shows that uncertain parameters do not present changes with the increment of K. This is because of the use of a robust estimator in the DR procedure.

5 Conclusion

In this first approach, two linear models with uncertainty were treated with RDR and a classic DR formulation, the analysis of results allows to conclude that:

Robust data reconciliation can treat models with uncertainty when outliers are present. In this sense, the Simple Method (SiM) can achieve accurate estimations of parameters and variables when measurements follow exactly or approximately the $\mathcal{N}$.

Uncertainty diminishes the SR. The analysis of RMSE curves for variables with different redundancy degree showed that SiM provided accurate estimation for all the types of variables. Because SiM takes advantage of temporal redundancy.

It is demonstrated that outliers deteriorate the estimations of measurements and uncertain parameters when classic DR is used. Conversely, the use of SiM allows obtaining good results for parameters and variables estimations independently of the presence and magnitude of outliers.

Model 2 shows that the use of temporal redundancy in the LS problem allows achieving the most accurate results for measurement that follows the $\mathcal{N}$. However, the presence of outliers deteriorates the estimations accuracy of measured variables and uncertain parameters.

Regards the robust procedure, SiM gives unbiased estimations for all the variables and parameters for the outlier magnitudes analyzed. Therefore, implementing RDR procedures is a suitable alternative to treat models with uncertainty. Future research will address nonlinear models and explore uncertainty caused by dynamics and uncertain parameters when measurements follow approximately the $\mathcal{N}$.

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Biogás En Neuquén, Una Alternativa

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Resumen. La cantidad de residuos aumenta con la población y es un problema creciente en nuestra sociedad. La posibilidad de producir biometano es una alternativa amigable con el medio ambiente. En Neuquén la fracción orgánica de los residuos FORSU alcanza el 44 % y es una potencial fuente de energía de biogas.

La cantidad de éste, se puede medir empleando el método de la jeringa y tiene la ventaja de ser un procedimiento experimental de bajo costo. El presente trabajo consistió en comparar la cantidad de gas generado en función de la concentración de sólidos totales. Su potencial es el volumen de biogas producido por la cantidad de materia prima expresada como sólidos volátiles. En este ensayo se usó la fracción orgánica de los residuos como sustrato (FORSU) y el agua residual de laguna anaerobia (AR LA) como inóculo, empleando jeringas de 60 ml a 35 °C con concentraciones de sustrato 5, 10, 15, 20 y 40 % de ST (sólidos totales) de FORSU y 10 ml de inóculo de agua residual de laguna anaerobia (AR LA).

Además, para la concentración de 5% y 20% se determinó un mayor potencial de biogás.

Palabras clave: Residuos, Fracción orgánica de los residuos FORSU, potencial de biogas, método de jeringa.

1 Introducción

El problema de la basura es un tema de interés mundial que está asociado a las actividades humanas [20]. Asimismo, el incremento de la población genera un aumento de la producción de los residuos y, por lo tanto, se deben enfrentar serias dificultades debido a estos [26]. Por ejemplo, los desechos generan organismos patógenos, vectores, enfermedades y contaminación ambiental [2]. En particular, cuando se arrojan los desechos de comida directamente al vertido, estos producen afectaciones negativas en el medio ambiente [24].

Una alternativa a este problema es el uso de la digestión anaerobia (DA) para transformar la fracción orgánica de los residuos en recursos, es decir, en metano y compost. La DA ocurre en forma natural, es una de los tecnologías más antiguas y común para producir energía a partir de biomasa [10]. La misma consiste en la descomposición de la materia orgánica en ausencia de oxígeno molecular. Es un proceso biológico de complejas reacciones bioquímicas asociadas a la actividad bacteriana de determinadas especies, por ende, tiene una fuerte dependencia de la composición del sustrato [3].

La información de la composición de los residuos es fundamental para la gestión y tratamiento de los mismos [25]. Estos datos se recopilan aplicando una metodología estandarizada para la caracterización de desechos domiciliarios [1].

En Argentina, en el año 2015, para una población 44.226.652 de personas se generaron 44.623 tn/d de residuos sólidos urbanos (RSU), mientras que en la Provincia del Neuquén con 550.344 habitantes se produjeron un total 455 tn/d [6]. A su vez, particularmente en la ciudad que lleva el mismo nombre, en ese año habían 245.419 personas [15] y la producción de RSU era de 209 tn/d. Cabe destacar, que en la ciudad de Neuquén el 44 % corresponde a la fracción orgánica de los residuos (FORSU) que es la constituida principalmente por restos de comida y cocina, cuyas características son heterogéneas.

Esta cantidad de residuos al ser transformado puede contribuir a una economía circular, es decir, "reducir, reutilizar y reciclar" [12]; lo que ayuda a disminuir el impacto negativo asociado a las actividades humanas.

El presente estudio tiene por objetivo determinar la cantidad de biogás a partir de FORSU de la ciudad de Neuquén usando como inóculo una agua residual de laguna anaerobia ARLA y un método experimental denominado test de Hohemheim HBT; si tenemos en cuenta que el potencial de biogas consiste en determinar el biogas generado para el inoculo seleccionado [11] se puede hallar la concentración optima de sólidos la mayor producción.

2 Materiales y métodos

2.1 Toma de muestra y composición de residuos

En Argentina la norma de referencia para la clasificación de residuos domésticos es ASTM D5231, dado a que es la fuente de datos disponibles [25]; la misma describe un método de cómo medir la composición de los residuos sólidos urbanos sin procesar, usando clasificación manual. Además, establece el proceso de recolección de una muestra de RSU representativa, así como, la reducción de datos y el.reporte de resultados.

Luego de la aplicación de la norma estandarizada, se tomó una muestra compuesta de la FORSU.,La cual fue transportada desde el centro de transferencia del Neuquén al laboratorio de Bioprocesos de la Universidad Tecnológica Nacional Facultad Regional Neuquén.para su conservación. Inmediatamentese redujo el tamaño cortando en trozos de 2 cm y se secó a 60°C hasta peso constante. Según lo que menciona Carneiro [5] esta instancia de secado es una etapa previa para poder triturar y homogeneizar los residuos, porque permite mantener sus propiedades. Luego de enfriar la muestra se

guarda en la heladera a 4 °C. Al momento del ensayo la muestra de FORSU se prepara con agua destilada y se tritura con miniprimer, de manera que quede homogénea.

Y en el caso de la muestra de agua residual de laguna anaerobia (ARLA), empleada como inóculo, se recolectó de la planta de tratamiento de efluente de la localidad de Plaza Huincul EPAS.

2.2 Caracterización de residuos

Se determinó en las muestras bajo normas estandarizadas: sólidos totales, sólidos volátiles, pH, conductividad y demanda química de oxígeno DQO; los métodos usados se resumen en la Tabla 1.

Los sólidos totales (ST) son los residuos de material que quedan en un recipiente después de la evaporación de agua en estufa a 103-105 ºC y los Sólidos fijos o cenizas corresponden a los residuos sólidos remanentes del calentamiento a 550 ºC. Mientras, los sólidos volátiles corresponden a los compuestos perdidos o volatilizados durante la calcinación a 550 ºC.

El pH es la medida de concentración de protones. En los residuos urbanos, es un parámetro que está asociado al origen y el estado de descomposición de la fracción orgánica. Por su naturaleza, presenta un pH ácido [19] En este estudio el pH se determinó con un pHmetro Hanna HI8424 previamente calibrado con soluciones amortiguadoras de pH=4,00 pH: 7.01 y pH=10 [8].

La conductividad es una expresión numérica de la capacidad de una solución para transportar una corriente eléctrica. Por lo tanto, es un valor que depende del total de iones que existe en la solución. En este estudio la conductividad se midió usando un conductímetro portátil Aquacombo.

La demanda química de oxígeno DQO es la cantidad de materia orgánica susceptible a ser oxidada por medio químico. Se utilizaron medir la DQO, los siguientes elementos: tubos de digestión HACH comerciales de 16 x 100 mm cuya capacidad es de 10 ml , un termoreactor Velp Eco8 para 150 + 2 º C y un espectrofotómetro Metash UV-Visible para leer a 600 o 420 nm.

Tabla 1. Resumen de técnicas usadas para análisis de FORSU y ARLA.

Parámetro	Unidad	Norma
Sólidos totales	%	Standard Method 2540B 17th Ed (APHA 1989)
Solidos volátiles	%	Standard Method 2540B 17th Ed (APHA 1989)
DQO	mg/l O_2	Standard Method 17th Ed (APHA 1989).
pH		Norma Boliviana de Residuos Sólidos 747.
Conductividad	mS/cm	Standard Method 2510B 17th Ed (APHA 1989)

2.3 Adaptación del inóculo

La muestra de ARLA luego de recolectarla se guardó por 1 semana en la cámara termostática a 35°C, para adaptarla a la temperatura del ensayo [14]. Se verifica la actividad del inoculo diariamente mediante su desgasificación. De esta manera se asegura que el inóculo este activo en condiciones operacionales definidas.

2.4 Ensayo de potencial de biogás por el método de jeringa

El método empleado para la determinación del biogás es el de Hohenheim denominado HBT [7], el cual consiste en utilizar jeringas como biodigestores a las cuales se les agrega el sustrato y el inóculo. Luego, se ajusta el émbolo sin que quede aire y se sella para evitar pérdidas.
Para mantener la temperatura constante se construyó una cámara térmica en el laboratorio de Bioprocesos de la Universidad Tecnológica Nacional Facultad Regional Neuquén, que utiliza un sistema de control Arduino y un caloventor 2000 watt, El ensayo se mantiene a 35°C y se registra el volumen generado de biogás en tiempo determinado,

Para la caracterización se emplean 3 réplicas con la misma concentración de residuos. Se usaron jeringas plásticas de 60 ml descartables. Las concentraciones ensayadas fueron: 5%, 10%, 15%, 20% ,40% ST de FORSU y una grupo, usando inóculo solo. La producción del biogás se comprueba mediante llama.

3 Resultados y discusiones

Los valores de la composición de residuos varían según la población, sus costumbres y poder adquisitivo. La fracción orgánica es el porcentaje más elevado de 44.2 % como se observa en la Tabla 2. En general se aprecian valores altos de FORSU en países subdesarrollados.

Tabla 2. Caracterización de residuos ciudad Neuquén ASTM D5231-92 (2016)

N=60	RSU-NQN
Papel	5.2
Carton	6.0
Plástico	10.9
FORSU	44.2
Ferrosos	0.5
Aluminio	0.6
Vidrio	4.6

En Latinoamérica según Sáez (2014) “el porcentaje de material putrescible es elevado”, y según los datos publicados en este artículo la fracción orgánica de los residuos oscila entre un 44% y 75%. Tomando datos de ciudades de Argentina con una población

entre 200 y 500 mil habitantes, como se muestra en la Tabla 3; se observan variaciones entre 17,22% y 45,61% de FORSU. El promedio de las mismas es 34.91 % [9] lo que evidencia que la cantidad de FORSU en Neuquén es un 5% más alta que el promedio.

Table 3. Cantidad de FORSU generado en Argentina por ciudad (2015). Elaborado a partir (Deluca y Giorgi, 2015).

CIUDAD	POBLACIÓN hab.	FORSU %
Avellaneda	342.677	45,61
Esteban Echeverria	300.959	31,85
José C. Paz	265.981	34,75
Malvinas Argentinas	322.375	35,61
Morón	321.109	33,64
San Isidro	292.878	35,44
San Miguel T	276.190	32,94
Tigre	376.381	31,46
Tres de Febrero	340.071	17,22
Vicente López	269.420	32,20
Escobar	213.619	31,37
Pilar	299.077	33,49
La Pampa	318.951	40,24
Ciudad de Neuquén	260.838	44.20

Tabla 4. Caracterización de residuos y aguas residuales.

N=3	FORSU-NQN	AR LA
pH (20°C)	5.16	7.39
Conductividad (21°C)	2 ms/cm	1002 us/cm
Sólidos Totales (ST)	67.12 %	0.687 mg/l
Sólidos volátiles (SV)	17.37 %	0.171 mg/l
DQO mg/l O_2	13017±152	6839+-213
Acidez	783±29 mg/l $CaCO_3$	93±29 mg/l

En la Tabla 4 se muestran los resultados obtenidos para la FORSU de la ciudad de Neuquén, como así también, para agua residual de laguna anaerobia AR LA. En el caso del pH tienen un valor de 5,16 indicando un carácter ácido. Los sólidos totales de la FORSU-NQN tienen un valor de 67,12% ST y son mayores que los expuesto en la Tabla 5, por ejemplo, el valor más alto es el de 38,8% ST [16], en el caso de los sólidos volátiles el porcentaje en este estudio es menor que en los presentados en la Tabla 5.

La variación en la composición de los desechos cambia con los hábitos y costumbres de cada población, y esto, se evidencia en los distintos estudios. Por lo cual, la elevada variabilidad hace necesaria la caracterización de las materias primas [20].

En la Tabla 5 se muestra que a mayor temperatura mayor producción de biogas; sin embargo, para este ensayo se elogió una temperatura de 35°C porque permite un proceso más estable en la producción de biogas.

Tabla 5. Caracterización de residuos y aguas residuales.

SUSTRATO	INÓCULO	T	SV	ST	BIOGÁS	Referencia
		°C	gr/kg	gr/Kg	ml CH4/ gr SV	
FORSU	LA	35	326.2	388.3	221	[16]
RCC	LA	55	234,24	244	441	[18]
RFV	LA	37	48,97	59	459	
FORSU	LA	37	322,14*	354	430	
RAS	LA	55	8	10,32	678	[13]
FORSU	LA PTAR	30	93016.67*	113036.7*	179,19	[19]
FORSU	LA PTAR	35	34,6	35,83	127,8	[22]
RPC	LA RAFA	37	253	290	600	[23]

FORSU: fracción orgánica de los residuos; RCC: residuos cocidos de cocina; RAS: residuos de alimento de supermercado; RPC: residuos de poda y comida; LA: lodo anaerobio; PPTAR: planta de tratamiento de agua residual y RAFA: reactor anaerobio de flujo ascendente. Léase*mg/l

Los resultados del potencial de biogas se representan en la Figura se observa que hay mayor acumulación de biogas para las concentraciones de 5% y 20% de FORSU con inóculo ARLA. De acuerdo Yi et al. (2014) [27] “a medida que aumentan los sólidos totales aumenta la cantidad de biogas acumulada”, esta condición se evidencia para las concentraciones de 10%, 15% y 20%

Sin embargo, de acuerdo a este ensayo, el biogas acumulado es similar para un 5% y 20 % de ST FORSU. Esto se explica para concentraciones de sustrato e inoculo menores a 1[4], como sucede del 5% FORSU, en el cual se favorece la producción e biogas [4].

En el caso del 40% de FORSU no se produjo biogas, y se infiere que se debe a alguna sustancia inhibidora. Dado que cuando se aumenta la carga orgánica se presentan efectos que evitan la generación de metano [17]

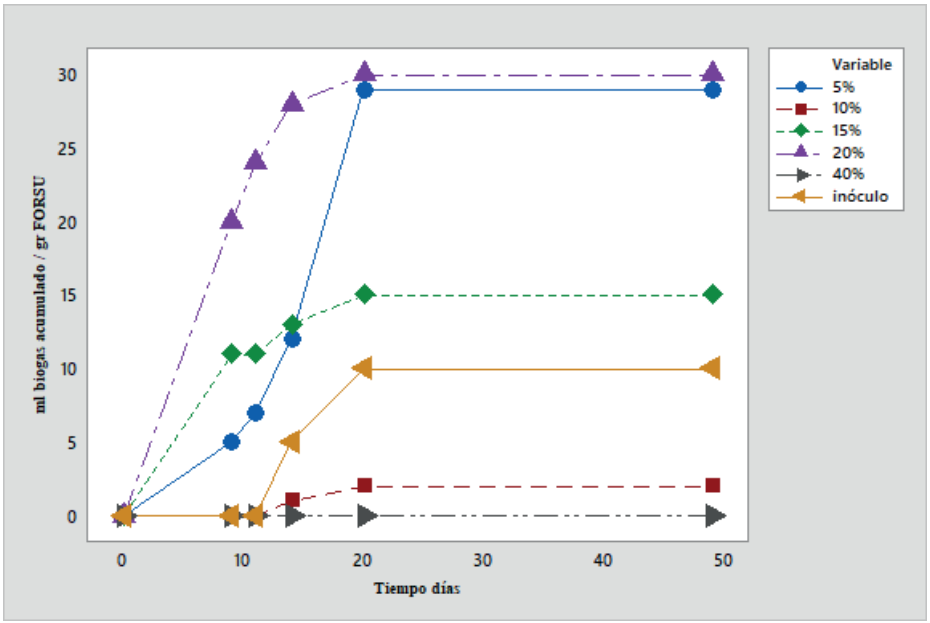

Fig. 1. Cantidad de biogás ml por día.

4 Conclusión

La fracción orgánica de los residuos del Neuquén es la fracción más significante de los residuos municipales y conforma un 44 % del total de los residuos. Según la caracterización, la muestra FORSU n=3; pH 5,18±0, Conductividad: 2ms/cm2, ST 67.12 %, SV: 17.37 %, DQO: 13017 ± 152mgO/l, Acidez total: 783± 29 mg/l CaCO3, NTK 11%. El inóculo empleado n=3 ARLA pH 6±0, Conductividad: 1002 ms/cm2, ST 0.687mg/l, SV: 0.171 mg/l, Acidez total 93± 29 mg/ l CaCO3.

La cantidad de biogas acumulada es similar para concentraciones de 5 y 20 % ST FORSU.

La cantidad de biogas acumulada para 10, 15 y 20 % ST FORSU aumenta con el aumento de los sólidos totales.

No se evidenció producción de biogas en el ensayo con 40% de sólidos.

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Tendencias climáticas de la Región Pampeana (Argentina) durante 1960-2019

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Resumen. La Región Pampeana es una de las áreas más productivas de la Argentina y por ello muy dependiente de las condiciones climáticas. El conocimiento de su variabilidad climática es esencial para orientar políticas destinadas a mejorar la calidad de vida de la población y el ambiente. El objetivo de este estudio fue analizar las tendencias de la precipitación y la temperatura durante las últimas seis décadas. Se utilizaron series de datos diarios de 50 estaciones meteorológicas durante el período 1960-2019. Luego, se analizó la tendencia termo-pluviométrica a escala local y regional, aplicando el test de Mann Kendall. La Región Pampeana presentó un aumento de las precipitaciones de 116 mm en los últimos 60 años, mientras que la temperatura mostró tendencias positivas y significativas en la mayor parte del área de estudio. Se identificó un aumento térmico regional superior a 1 ºC. La información generada en esta investigación es esencial para que los actores locales y tomadores de decisiones diseñen planes de adaptación a las condiciones a las que está expuesta el área de estudio.

Palabras clave: test de Mann Kendall, precipitación, temperatura.

1 Introducción

En la actualidad, el cambio climático y el calentamiento global son los fenómenos que mayores impactos ambientales generan a escala global (Wang et al., 2015). Particularmente, la variabilidad climática tiene efectos negativos sobre la calidad de vida de la población y el desarrollo de sus actividades económicas, principalmente las agropecuarias (Sun et al., 2016). En este contexto, la Región Pampeana (Argentina) adquiere gran relevancia dado que es una de las regiones productivas más importantes del país. Está localizada en el centro-este de Argentina y tiene una extensión de 613.532 km^2 (Fig. 1). Por ello, el objetivo de este estudio fue analizar las tendencias de la precipitación y la temperatura durante los últimos 60 años. La finalidad de este

trabajo es la de proporcionar información destinada a generar políticas públicas orientadas al manejo de los recursos naturales y a garantizar la sustentabilidad de las actividades agropecuarias.

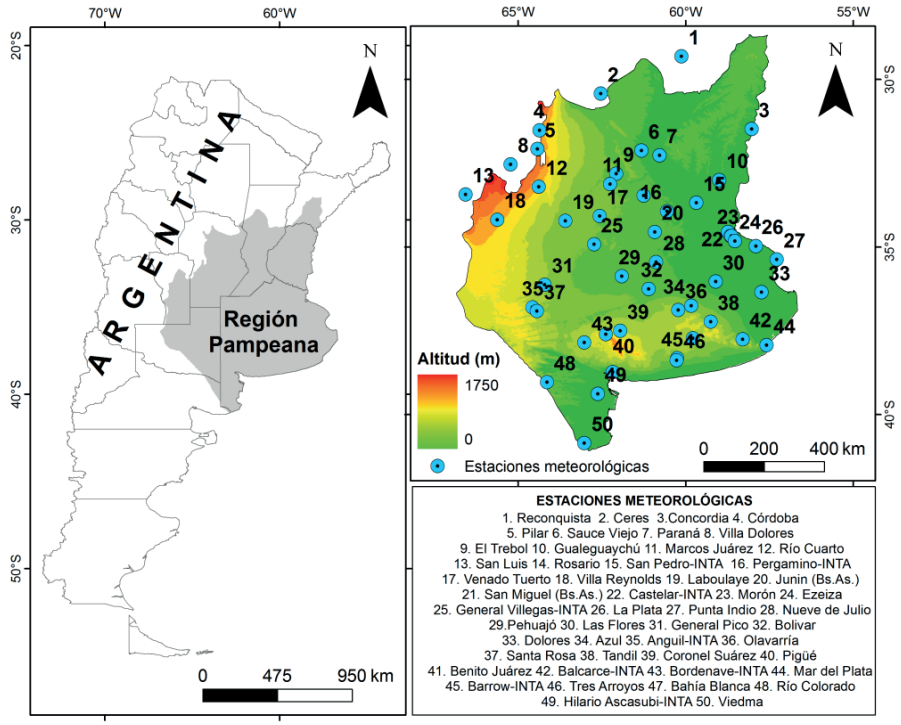

Fig. 1. Localización del área de estudio y de las estaciones meteorológicas utilizadas.

2 Metodología

Se recolectaron datos diarios de temperatura media, máxima y mínima y precipitación de 50 estaciones meteorológicas pertenecientes al Servicio Meteorológico Nacional (SMN) y al Instituto Nacional de Tecnología Agropecuaria (INTA) (Fig. 1). En una primera instancia, se evaluó la homogeneidad y la calidad de la información para completar las series de tiempo del período 1960-2019, aplicando un Análisis de Componentes Principales. Para ello, se consideraron las estaciones con datos faltantes y/o registros atípicos superiores al 5 % con sus vecinos más próximos. Como resultado, se obtuvo una matriz de confusión necesaria para crear las componentes principales. Se utilizó la matriz de Spearman para analizar la información y detectar la correlación entre ellas.

Como resultado, se obtuvo un nuevo set de variables resultante de la combinación lineal de las variables originales, capturando la mayor parte de la varianza original observada en los datos medidos *in situ*. Con esta información se completaron las se-

ries originales. Posteriormente, se estudiaron las tendencias con el test de Mann-Kendall (Mann, 1945; Kendall, 1975), a través de utilización del paquete Trend en el software R Studio. La tendencia se analizó a escala local y regional y la variación espacio-temporal fue graficada en un Sistema de Información Geográfica (ArcGIS 10.5).

3 Resultados

A escala local, la temperatura máxima se incrementó en todas las estaciones meteorológicas, con tendencias mayormente significativas. La temperatura mínima registró una tendencia hacia el calentamiento, aunque en el 36 % del área las tendencias fueron negativas. Estas zonas se corresponden con las áreas de mayor altura. La temperatura media presentó una tendencia al incremento, exceptuando la región sudeste (Fig. 2) del área de estudio. La temperatura máxima presentó el mayor incremento regional que fue estadísticamente significativo (+1,8 ºC en los últimos 60 años, $p < 0,01$). La temperatura mínima aumnetó en menor medida, pero también mostró evidencia estadística (+1,1 ºC en el período 1960-2019, $p < 0,01$). Por último, la temperatura media regional aumentó 1,2 ºC en el período 1960-2019 con significancia estadística

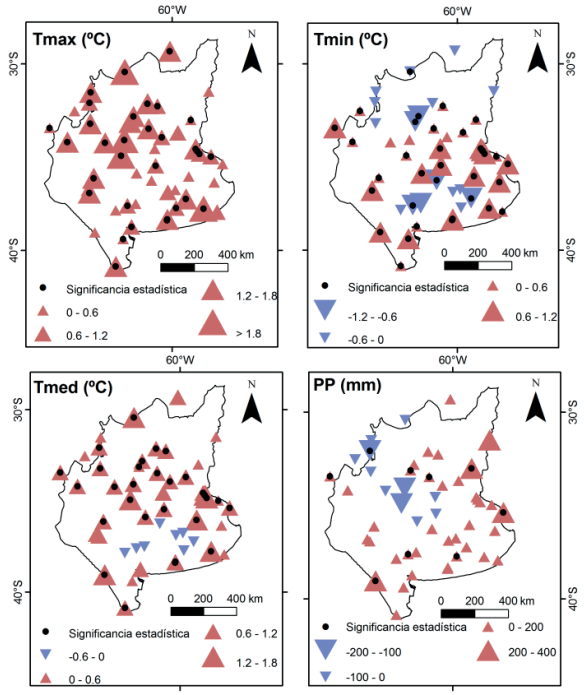

Fig. 2. Tendencia de la temperatura máxima, mínima, media y la precipitación en la Región Pampeana (Argentina) durante el período 1960-2019. Tmax. Temperatura máxima; Tmin. Temperatura mínima; Tmed. Temperatura media; PP. Precpitación.

La precipitación presentó una tendencia positiva en el 78 % de la Región Pampeana. El área localizada en el centro y noroeste mostró una tendencia negativa, registrando una disminución de 67 mm en las últimas seis décadas. Los mayores incrementos se identificaron en el noreste, en donde aumentó 398 mm/período. A pesar de ello, los cambios fueron estadísticamente significativos sólo en el 18 % de la región (vea Fig. 2). A escala regional, se identificó una tendencia positiva que no fue estadísticamente significativa ($p > 0,05$), marcando un incremento de 116 mm en los últimos 60 años.

4 Conclusión

Se analizó el comportamiento local y regional de la temperatura y la precipitación en la Región Pampeana durante 60 años. Las tendencias regionales de la temperatura identificaron que la región está expuesta a los efectos del calentamiento global. Tanto las temperaturas máximas y mínimas registraron un incremento superior a 1 ºC. Por otro lado, la precipitación mostró un patrón espacial heterogéneo, con menor significancia estadística. Sin embargo, se observó en el análisis regional que presentó una tendencia positiva. Los resultados obtenidos sirven de base para el orientar las propuestas de manejo del territorio destinadas a reducir y mitigar los efectos negativos que la variabilidad climática tiene sobre los ecosistemas y sobre la salud de la población y sus actividades económicas.

Agradecimientos

Se agradece a la Universidad Nacional del Sur (UNS) y al Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) por el financiamiento de la presente investigación. Además, se destaca al Servicio Meteorológico Nacional (SMN) y al Instituto Nacional de Tecnología Agropecuaria (INTA) por brindar la información climática analizada en este estudio.

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Variabilidad climática de la Región Pampeana (Argentina) en el contexto de cambio climático

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Resumen. El objetivo de este estudio fue analizar la tendencia de la temperatura y la precipitación actual y futura de la Región Pampeana (Argentina). Se utilizó información de precipitación y temperatura máxima y mínima *in situ* y datos futuros provistos por el modelo CCSM4. Se definieron cinco períodos de estudio: presente (2000-2019), futuro cercano RCP 4.5 y RCP 8.5 (2020-2039) y futuro lejano RCP 4.5 y RCP 8.5 (2080-2099). En cada uno de ellos, se calculó la tendencia termo-pluviométrica con el test de Mann Kendall. El área de estudio mostró señales de calentamiento atmosférico con significancia estadística en el presente y el futuro cercano y lejano bajo el escenario RCP 8.5. La precipitación tuvo tendencia negativa en el presente y se incrementó hacia el futuro. La variabilidad termo-pluviométrica impacta negativamente sobre la producción agropecuaria. Por lo tanto, estos resultados son esenciales para los tomadores de decisiones y los productores agropecuarios, dado que sirven de base para el diseño de medidas de mitigación orientadas a reducir los impactos de la variabilidad climática sobre las economías regionales.

Palabras clave: precipitación y temperatura actual y futura, datos *in situ* y modelados, producción agropecuaria.

1 Introducción

El calentamiento global, principal causa del cambio climático, ha ocasionado el incremento de la temperatura atmosférica impulsada por la emisión de gases de efecto invernadero (Padhiary et al., 2018). Como consecuencia, se han registrado cambios en el régimen y la intensidad de las precipitaciones producto de una mayor concentración del vapor de agua en la atmósfera (Muthuwatta et al., 2018). La Región Pampeana (613 mil km^2, Argentina) (Fig. 1) es el área productiva más importante del país y además es altamente vulnerable a las variaciones climáticas. Por ello, el objetivo de este estudio fue analizar la tendencia de la temperatura y la precipitación actual y futura de la Región Pampeana. Los resultados de esta investigación servirán de base para el diseño de medidas de mitigación orientadas a reducir los impactos de la variabilidad termo-pluviométrica sobre las economías regionales.

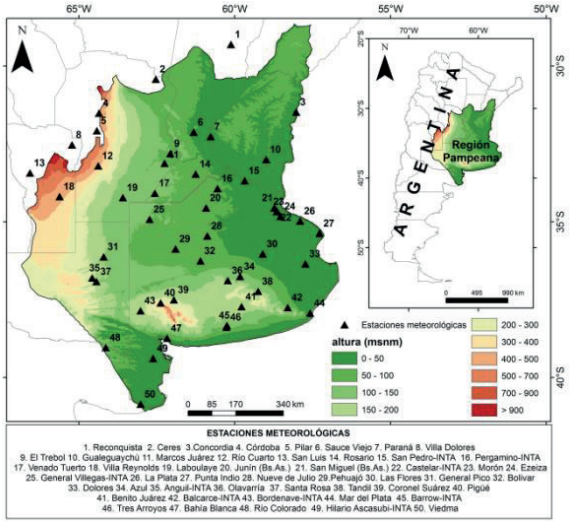

Fig. 1. Topografía y localización a de la Región Pampeana (Argentina) y de las estaciones meteorológicas utilizadas.

2 Método de trabajo

Se utilizaron datos mensuales de precipitación, temperatura máxima y mínima de 50 estaciones meteorológicas localizadas en la Región Pampeana durante el período 2000-2019, denominado período presente (Fig. 1). Estos fueron cedidos por el Servicio Meteorológico Nacional y el Instituto Nacional de Tecnología Agropecuaria. Por otro lado, se utilizaron datos provistos por el modelo global CCSM4 (Community Climate System Model 4) perteneciente al Centro Nacional de Estudios de la Atmósfera (NCAR, Estados Unidos). Estos datos fueron obtenidos de la página del Centro de Investigaciones del Mar y la Atmósfera de Argentina (CIMA - http://3cn.cima.fcen.uba.ar). La selección de este modelo se basó considerando los resultados de la validación de 24 modelos realizado por el CIMA, quienes indicaron que este modelo es el más preciso para representar las condiciones hídricas y térmicas futuras de la Región Pampeana. La información fue analizada en dos períodos de tiempo. Uno se denominó futuro cercano (2020-2039) y el otro futuro lejano (2080-2099). Ambos fueron considerados en dos escenarios de concentración de gases de efecto invernadero en la atmósfera (RCP – Representative Concentration Pathways, por sus siglas en inglés). Finalmente, se analizó la tendencia de los tres índices en los cinco períodos de estudio. Para ello, se aplicó la prueba no paramétrica de Mann-Kendall (Mann, 1945; Kendall, 1975), mediante la utilización del paquete Trend en el software R Studio.

4 Resultados

La tendencia y la significancia estadística regional de la temperatura máxima, mínima y la precipitación durante los cinco períodos analizados se muestra en la Tabla 1, mientras que la variación espacial se presenta en la Figura 2. La temperatura máxima

mostró, durante el presente, tendencia positiva en el 98 % del área de estudio (Tabla 1). El incremento regional fue 1.1 °C y la significancia estadística fue observada en el 82 % de la región (Tabla 1). El centro de la región fue el que presentó los mayores incrementos, que fueron de hasta 2.1 °C durante los 22 años analizados (Fig. 2). Hacia el futuro, los cambios con evidencia estadística más importantes de este índice, se registraron bajo el escenario RCP 8.5 en ambos períodos. El aumento promedio fue 0.6 °C (Tabla 1). En el futuro lejano, el incremento regional fue mayor que en el futuro cercano y el presente (1.4 °C) y la tendencia fue positiva y estadísticamente significativa en la totalidad del área de estudio (Tabla 1). Estos cambios térmicos fueron más importantes en el N y W (Fig. 2).

La temperatura mínima presentó tendencia positiva en todos los períodos analizados. Sin embargo, fue significativa en el presente y el futuro lejano y cercano bajo el escenario RCP 8.5 (Tabla 1). El presente mostró tendencia positiva en el 68 % del área de estudio, siendo estadísticamente significativo en el 76 %. El aumento regional fue 0.5 °C (Tabla 1). Durante el futuro lejano y cercano RCP 8.5, se registró un 98 y 100 % de tendencia positiva, respectivamente. La región tuvo un aumento de la temperatura mínima de 0.6 °C en el futuro cercano y 0.9 °C en el futuro lejano (Tabla 1). Estos incrementos no presentaron una preferencia espacial en la zona de estudio (Fig. 2).

Tabla 1. Número de estaciones meteorológicas de la Región Pampeana que presentaron disminución (D) o incremento (I) de la temperatura máxima, mínima y precipitación durante los cinco períodos analizados. N°: número de estaciones meteorológicas; S: significancia estadística. P. Reg.: promedio regional.

Indice	Presente					Futuro cercano RCP 4.5					Futuro lejano RCP 4.5				
	P. Reg.	D		I		P. Reg.	D		I		P. Reg.	D		I	
		N°	S	N°	S		N°	S	N°	S		N°	S	N°	S
Tmax (°C)	**1.1 ± 0.5**	1	0	49	40	**0.3 ± 0.2**	17	0	33	10	**-0.2 ± 0.1**	43	0	7	0
Tmin (°C)	**0.5± 0.4**	16	3	34	16	**0.3± 0.2**	14	0	36	10	**0.3 ± 0.1**	12	0	38	4
Prcptot (mm)	**-120± 91**	31	23	19	1	**90 ±54**	11	0	39	17	**75 ± 53**	22	2	28	7
Indice	**Futuro cercano RCP 8.5**					**Futuro lejano RCP 8.5**									
	P.Reg.	D		I		**P. Reg.**	D		I						
		N°	S	N°	S		N°	S	N°	S					
Tmax (°C)	**0.6 ± 0.4**	1	0	49	32	**1.4 ± 0.3**	0	0	50	50					
Tmin (°C)	**0.6 ± 0.2**	1	0	49	35	**0.9 ± 0.3**	0	0	50	50					
Prcptot (mm)	**63 ± 34**	19	7	31	21	**63 ± 50**	17	0	33	27					

La precipitación evidenció tendencia negativa sólo en el presente (Tabla 1). Esta situación se encontró en el 62 % del área de estudio (31/50), siendo estadísticamente significativa en el 74 %. En promedio, disminuyó 120 mm durante los 22 años analizados (Tabla 1). Durante el futuro cercano, el 62 % de las estaciones mostraron tendencia positiva y la significancia fue encontrada en el 68 %, mientras que en el futuro lejano la tendencia positiva se registró en un mayor número de estaciones meteorológicas (66 %). Finalmente, es importante destacar que en ambos futuros RCP 8.5, la precipitación presentó modificaciones espaciales importantes con respecto al presente (Fig. 2).

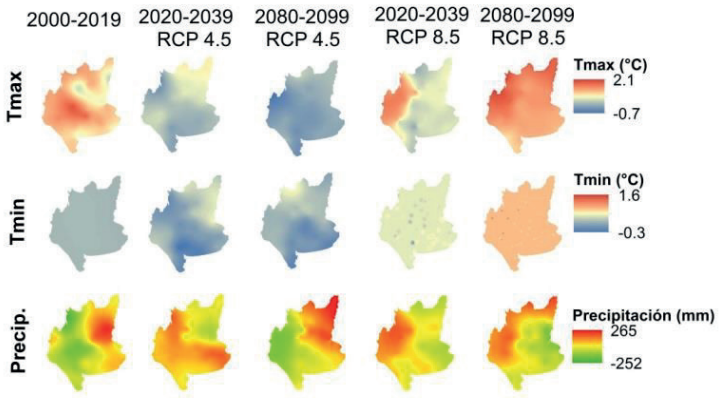

Fig. 2. Variación espacial de la temperatura máxima, mínima y la precipitación de la Región Pampeana durante los cinco períodos analizados.

5 Conclusión

Se analizó la tendencia de la temperatura máxima, mínima y la precipitación durante presente y el futuro en la Región Pampeana (Argentina) y se determinó las condiciones a las que el área de estudio estará expuesta en el futuro. La tendencia de los tres índices fue estadísticamente significativa en el presente y el futuro cercano y lejano bajo el escenario de mayor concentración de gases de efecto invernado (RCP 8.5). En estos tres períodos, se detectaron señales de calentamiento atmosférico que fueron de mayor magnitud en el futuro lejano bajo el RCP 8.5. La precipitación fue negativa en el presente y aumentó hacia el futuro. Por lo tanto, este trabajo presenta información esencial para los tomadores de decisiones y los productores agropecuarios que sirve de base para el diseño de medidas de mitigación orientadas a reducir los impactos de la variabilidad climática sobre las economías regionales.

Agradecimientos

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Disminución de la Disponibilidad de Agua Potable por Expansión de la Forestación, en el Sector Costero Oriental de la Provincia de Buenos Aires, Argentina

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Resumen. El agua es un recurso natural indispensable para la actividad humana. En acuíferos costeros de espesor y extensión limitados, las variaciones en el uso del suelo pueden condicionar la calidad y cantidad de agua disponible para la explotación, ya sea para uso industrial o para abastecimiento de la población. El objetivo de este trabajo es cuantificar la expansión de las áreas forestadas y el efecto de esta expansión sobre la disponibilidad de agua subterránea, en la localidad de Mar de las Pampas, Partido de Villa Gesell, Provincia de Buenos Aires. A partir de imágenes satelitales y fotografías aéreas, mediante el mapeo manual detallado de los tipos de cobertura en la zona de estudio, se realizó un análisis del uso del suelo para los años 1975 y 2014. Se calcularon balances hídricos a partir de datos de precipitación, teniendo en cuenta las propiedades hidrológicas características del terreno, para asignar un valor de recarga a cada tipo de cobertura. Los resultados indican una reducción de la recarga de un 26% durante el período 1975-2014, lo cual deberá tenerse en cuenta para la planificación del uso sustentable del recurso hídrico subterráneo, en una localidad actualmente en crecimiento.

Palabras Clave: Agua Subterránea; Calidad Ambiental; Manejo de Recursos Hídricos.

1 Introducción

Las zonas costeras revisten gran importancia desde un punto de vista económico y ambiental, debido a que las poblaciones humanas suelen ubicarse cerca o dentro del ambiente costero. Las poblaciones costeras ejercen modificaciones sobre las condiciones naturales del ambiente, lo cual tiene un gran impacto en el equilibrio costero [1]. Uno

de los recursos más afectados por estas modificaciones es el agua subterránea, especialmente cuando se trata de ambientes de dunas costeras que albergan lentes de agua dulce [2].

La evolución a través del tiempo del uso del suelo en una zona determinada, tiene un gran impacto en varios aspectos aplicados y en las actividades humanas que se desarrollen en dicha zona. Las imágenes satelitales han sido aplicadas con éxito al estudio espacial de distintos tipos de áreas, incluyendo zonas costeras, urbanas, forestadas y agrícolas. Entre otros, fueron llevados a cabo estudios de uso del suelo y cambios en el paisaje [3, 4]. Es frecuente el uso de Sistemas de Información Geográfica (SIG) en forma conjunta con las técnicas de sensores remotos, para cuantificar la variación temporal uso del suelo [5, 6].

Existen numerosas aplicaciones de los sensores remotos a los estudios hidrológicos e hidrogeológicos; entre ellas, se cuentan el análisis de la variación areal en el tiempo de cuerpos de agua superficiales [7, 8], la identificación de áreas de recarga y descarga naturales [9, 10] y de áreas adecuadas para la recarga artificial en regiones áridas [11].

Las características del suelo afectan directamente al ciclo hidrológico de una zona, dado que la cobertura del suelo controla los procesos de evapotranspiración, infiltración y escurrimiento superficial que atraviesa el agua proveniente de las precipitaciones. Debido a esto, algunos trabajos se centran en la cuantificación de variaciones temporales en la cobertura impermeable, producto de la urbanización [12, 13]. Otros trabajos se centran en las modificaciones en la cobertura forestal de una zona y su impacto hidrológico. La forestación es una actividad antrópica frecuente en ambientes de dunas costeras debido a que la implantación de bosques provee protección contra la erosión y facilita la fijación de las dunas [14]. Sin embargo, se reconocen efectos adversos de la forestación sobre el ciclo hidrológico, específicamente sobre los balances hídricos. La implantación de bosques aumenta la evapotranspiración y disminuye los excesos de agua, por lo cual se ve disminuida la recarga al sistema subterráneo [15-17].

Existen antecedentes de este tipo de estudios en la costa de la Provincia de Buenos Aires. Carretero y Kruse [18] realizaron un análisis de detalle del uso del suelo en San Clemente, entre los años 1958 y 2005. Se estimó una disminución en la recarga de 47% en la zona urbanizada. El mismo análisis fue llevado a cabo en Las Toninas y Santa Teresita entre 1987 y 2012; los resultados mostraron un 30% de reducción en la recarga [19]. Posteriormente, Carretero et al. [20] analizaron la variación en la recarga debida al cambio en el uso del suelo en el Partido de La Costa (que incluye a las localidades mencionadas anteriormente) para el período 1973-2010. En este caso, los resultados indicaron un 10% de reducción en la recarga para la totalidad del área estudiada, aunque la reducción es de un 18 y 30% cuando se focaliza en los centros urbanos. Más recientemente, Rodrigues Capitulo et al. [21] aplicaron una clasificación supervisada a imágenes satelitales Landsat 7 TM del año 2015, para identificar superficies forestadas y suelo desnudo en el Partido de Pinamar. Según los resultados, la recarga sería un 33% menor en las áreas forestadas, respecto de las no forestadas.

En el presente trabajo se analiza la evolución del uso del suelo en un sector de la costa bonaerense (Argentina), vinculando los aspectos geomorfológicos y forestales, como base para la estimación de las modificaciones en la recarga del agua subterránea. A pesar de la importancia del recurso hídrico en la planificación y gestión urbana, aún

no hay estudios de este tipo sobre la zona, de forma que este trabajo resulta de utilidad para iniciar la tarea de cuantificar las reservas de agua dulce en el acuífero freático.

1.1 Área de Estudio

La localidad de Mar de las Pampas se encuentra emplazada en la región geomorfológica conocida como Cordón Costero, en la costa atlántica de la Provincia de Buenos Aires, Argentina (Fig. 1). Se centra en los 37°19′26″ de latitud sur y 57°01′30″ de longitud oeste. Forma parte de Partido de Villa Gesell y limita al noreste con la localidad homónima. Hacia el sur, limita con la localidad de Mar Azul; hacia el noroeste, fuera de los límites del cordón costero, dentro de la llanura continental, se encuentra el partido de General Madariaga.

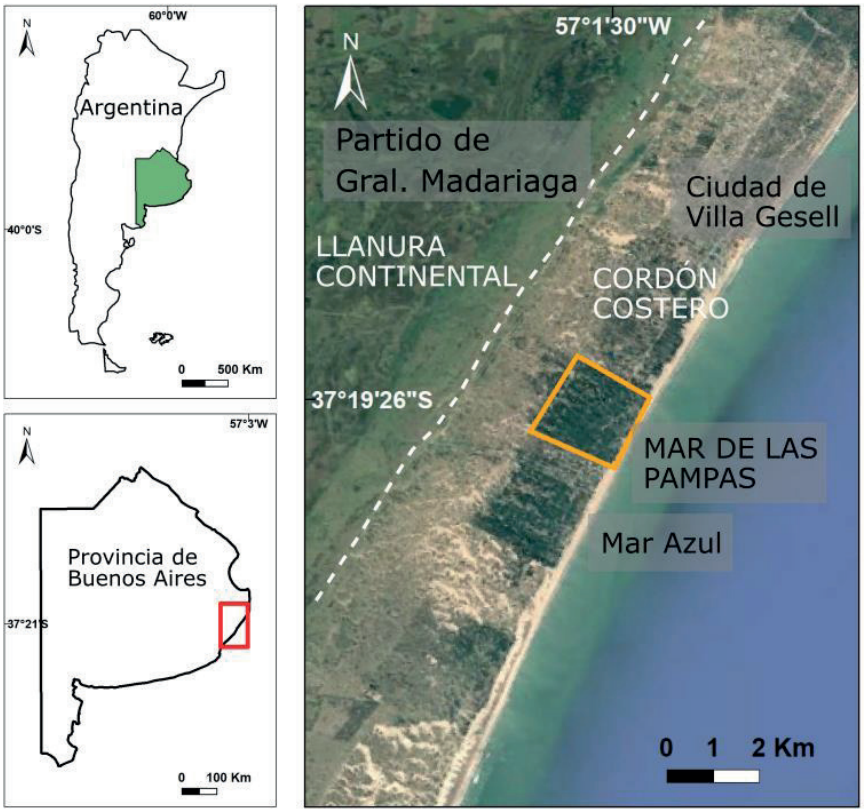

Fig. 1. ubicación del área de estudio.

Los trabajos de fijación de dunas en Mar de las Pampas comenzaron en 1957, pero recién en 1971 se aprobó el plan definitivo de forestación y trazado urbano, en el cual las calles y manzanas debían adecuarse a la morfología medanosa natural. En el año 2010, la población estable era de 1.797 habitantes [22]. Sin embargo, al tratarse de una

localidad balnearia, debe tenerse en cuenta el aumento estacional de la población debido a la avenida turística en la época estival.

El acuífero freático se aloja en el cordón arenoso, que fue construido durante el Holoceno como resultado de la acción conjunta de procesos costeros y procesos eólicos vinculados a la generación y migración de dunas costeras [23, 24]. El cordón costero presenta en esta región poco más de 3 km de ancho; y en el sector central las dunas se elevan hasta aproximadamente 20 msnm [25, 26]. El área de estudio se encuentra dentro de la Región II definida por el Consejo Federal de Inversiones [27]. Esta región presenta características geomorfológicas particulares, que tienen un fuerte impacto en su comportamiento geohidrológico. Rodrigues Capitulo [28] definió un modelo hidrodinámico para la localidad de Pinamar, que forma parte de la Región II y se ubica a pocos kilómetros de Mar de las Pampas. Según este modelo, la recarga de agua subterránea es de índole local y directa a partir de las precipitaciones. Dada la alta permeabilidad del sustrato arenoso, se considera nulo el escurrimiento superficial, de forma tal que los excesos de agua contribuyen en su totalidad a la infiltración. Una vez alcanzada la zona saturada, el agua se mueve desde la zona central del cordón hacia ambos bordes del mismo. Del lado oeste, una zona de interface separa el agua dulce del cordón costero del agua salobre contenida en los sedimentos de la llanura continental. Del lado este, se registra una interface entre el agua dulce y el agua salada del mar. Esta última fue identificada en el Partido de Villa Gesell por Hurtado et al. [29], mediante la realización de estudios geoeléctricos.

El acuífero costero constituye la única fuente de agua potable para la población. El aumento de la población estable y, especialmente, el desarrollo turístico de la zona, resultan en una creciente presión de explotación sobre el recurso hídrico. A su vez, debe tenerse en cuenta que el sistema costero presenta particularidades que lo hacen especialmente vulnerable respecto de los problemas con el agua, como son la posibilidad de intrusión salina y la sensibilidad a la contaminación por sobrebombeo.

2 Materiales y Métodos

La metodología de trabajo comprendió tareas de mapeo y manejo de datos en SIG (i.e., identificación de distintas unidades de mapeo, digitalización manual de las mismas, análisis multitemporal de su evolución para el período 1975-2014), así como otras propias de los estudios hidrológicos (realización de balances hídricos, asignación de un valor de recarga a los distintos tipos de cobertura del suelo en base a criterios hidrológicos, estimación de la recarga total en la zona de estudio para los diferentes escenarios analizados).

La base para el mapeo del uso del suelo fueron imágenes aéreas y satelitales. Se contó con fotos aéreas del año 1975 facilitadas por el Instituto Geográfico Nacional (IGN). Las imágenes satelitales del año 2014 fueron obtenidas de Google Earth. Se generaron mosaicos con los conjuntos de imágenes correspondientes a cada año, para poder visualizar en su totalidad el área de interés. Las imágenes así compuestas fueron introducidas en un SIG, donde se realizó su georreferenciación según el sistema de coordenadas POSGAR 2007 Transverse Mercator, Datum POSGAR 2007, Faja 6. El

área de mapeo coincide con los límites políticos de la localidad de Mar de las Pampas (Fig. 1). Hacia el sudoeste, noreste y noroeste, se tomaron como límite de mapeo las calles principales que actualmente bordean la localidad. En dirección sudeste, hacia al mar, el mapeo se realizó hasta el comienzo de la zona de playa.

2.1 Geomorfología

Las unidades geomorfológicas fueron definidas en la imagen del año 1975, sobre la base de la textura y tono (en escala de grises) observados en la imagen. Se identificaron dos unidades: (1) dunas costeras, caracterizadas por un tono claro correspondiente a la alta reflectancia de la arena seca, y (2) interdunas, caracterizadas por un tono más oscuro vinculado a la presencia de humedad superficial, y por una textura granular debida a la vegetación herbácea natural que se desarrolla en esas condiciones. Si bien las copas de los árboles pueden impedir puntualmente la observación directa de la superficie, entre las mismas puede identificarse una cobertura correspondiente a la clase (1) descripta, por lo que las áreas cubiertas por árboles fueron asignadas a la categoría de dunas costeras. La Fig. 2 muestra un ejemplo de las superficies de dunas costeras e interdunas.

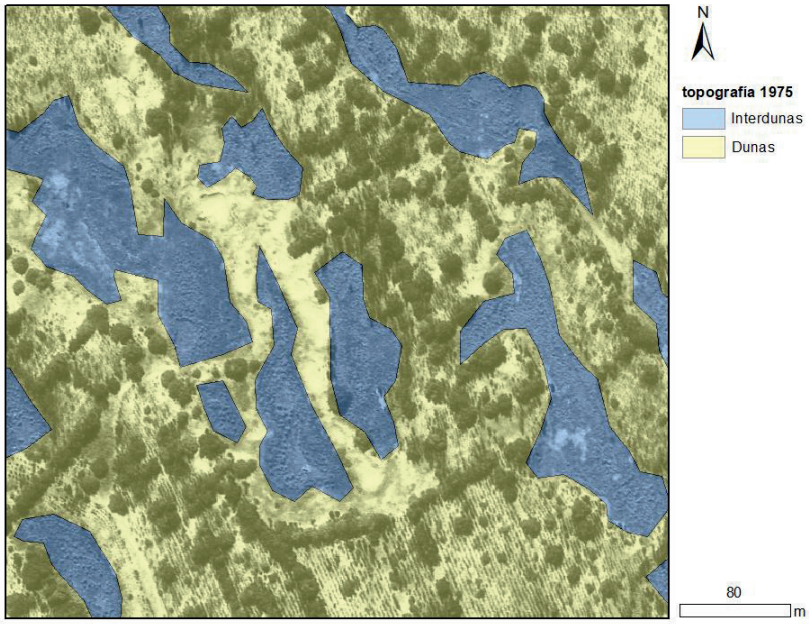

Fig. 2. dunas costeras e interdunas en el área de estudio.

2.2 Uso del Suelo

Se realizó la digitalización manual de las zonas de uso del suelo en los diferentes años a una escala de 1:2.000. El resultado fue la generación de archivos de tipo vectorial con polígonos que representan las diferentes zonas mapeadas. Los usos del suelo fueron definidos sobre la imagen de 1975, para luego extrapolar el criterio de mapeo a la imagen moderna. Dicho criterio consistió en la identificación visual de propiedades que permitieran asignar a la superficie una de las cinco categorías de uso del suelo consideradas, a saber: (1) nulo: no se observa acción antrópica. Incluye zonas de interdunas con tono oscuro por la presencia de arena húmeda y/o vegetación herbácea, así como zonas de alto albedo correspondientes al suelo arenoso desnudo, sin vegetación natural o artificial. (2) plantación inicial: zonas de dunas donde se observa la grilla de plantación de árboles, pero éstos aún no se han desarrollado. (3) ralo forestal: coexisten árboles de escaso desarrollo, apenas visibles en la fotografía aérea, con algunos árboles de mayor tamaño cuyas copas no se tocan entre sí. El suelo arenoso es visible en forma prácticamente continua. (4) medio forestal: similar a ralo forestal, pero con una mayor cobertura por parte de los árboles. Las copas frecuentemente se tocan entre sí, conformando líneas de forestación entrecruzadas; sin embargo, el suelo arenoso es aún visible. (5) denso forestal: las copas forman una cubierta coalescente prácticamente continua, con frecuentes pero pequeños espacios de raleo o cambios en la textura que indican diferentes etapas de desarrollo de los árboles y/o distintas especies.

El área total ocupada por cada categoría en los sucesivos años se obtuvo mediante la función Calculate Geometry presente en el SIG, que proporciona la extensión superficial de los elementos poligonales de formato vectorial incluidos en una capa.

2.3 Comparación Entre Desarrollo Forestal y Relieve

Resulta de interés conocer la evolución en la relación que guardan las variables relieve y uso del suelo a lo largo de la serie analizada. Originalmente, la forestación fue planificada en base a la geomorfología de la zona, con la intención de forestar únicamente las zonas altas (dunas costeras) y ubicar las calles y caminos en las zonas bajas (interdunas). Para determinar la distribución de clases de uso del suelo en las interdunas, así como en las dunas costeras, se realizó una intersección de las capas de uso del suelo y relieve, para cada año analizado.

2.4 Realización de Balances Hídricos

La importancia de cuantificar los excesos en el balance hídrico radica en que la totalidad de dichos excesos constituye la única recarga del acuífero freático, dado que, en el cordón medanoso, el escurrimiento superficial tiende a cero [21].

Para determinar los excesos de agua se realizaron balances hídricos según Thornthwaite y Mather [30], a partir de datos diarios de precipitación del Servicio Meteorológico Nacional en Villa Gesell. La serie de datos corresponde al período 1997-2016; dado que las precipitaciones no han cambiado significativamente en este período, estos

datos se consideran representativos de la lluvia en la región [21]. Se asumió que la intercepción contribuye en un 100% a la evapotranspiración (ET).

Se usaron valores medios diarios de evapotranspiración de referencia (ETo), estimados con la ecuación FAO Penman–Monteith [31]. La evapotranspiración potencial (ETc) puede calcularse mediante la ecuación (1):

$$ETc = ETo \times Kc \qquad (1)$$

donde ETc es la máxima evapotranspiración de la cobertura; ETo es la evapotranspiración de referencia y Kc es el coeficiente de cultivo o de cobertura.

La capacidad de campo (CC) media para este suelo dominado por arena fue de 160 mm/m, siguiendo a Falasca y Forte Lay [32], que definen un valor de 140 y 180 mm hasta una profundidad de 1 m a lo largo de la costa arenosa bonaerense. Se consideraron dos casos: suelo desnudo (suelo arenoso con escasa vegetación o sin ella) y forestal (suelo cubierto por un bosque de coníferas). En el primer caso, la profundidad efectiva asignada para el balance fue de 0,25 m y por lo tanto quedó definida una CC de 40 mm, dado que el efecto de la evapotranspiración no puede penetrar más profundo. En el segundo caso debió tenerse en cuenta una exploración de raíces de más de 1 m, ya que se trata de un bosque bien establecido. Por ello, se asignó una profundidad de 1,25 m, que derivó en una CC de 200 mm en el balance.

Se determinaron valores de Kc de acuerdo a FAO [31]. Para la zona de suelo desnudo el valor fue variable a lo largo del año; mientras que para la zona forestal se tomó Kc=1 constante todo el año.

Los valores de ETo y Kc adoptados fueron procesados con el software AGROAGUA v.5.0 [33]. Esta aplicación permite obtener balances hídricos mensuales a partir de variables como la capacidad de campo, evapotranspiración potencial diaria y precipitaciones diarias. Los balances mensuales así obtenidos fueron agrupados en valores anuales, para luego calcular un valor anual promedio de precipitación y de excesos para las categorías de recarga consideradas.

2.5 Agrupación de Usos del Suelo Según Criterio Hidrológico y Obtención de Valores de Recarga

Las características superficiales del terreno condicionan las posibilidades de infiltración del agua aportada por las precipitaciones. Es posible obtener un valor de recarga total para la zona de estudio, aplicando los balances hídricos explicados previamente a las clases de desarrollo forestal identificadas en el mapeo, y conociendo la distribución espacial de éstas.

Para esto, se agruparon las categorías de uso del suelo según un criterio hidrológico, de forma tal que las categorías nulo, plantación inicial y ralo forestal corresponden a la categoría de recarga de suelo desnudo, mientras que medio forestal y denso forestal se agrupan bajo la categoría hidrológica forestal. La Fig. 3 muestra la correspondencia entre las zonas de uso del suelo y las superficies de recarga para el año 1975.

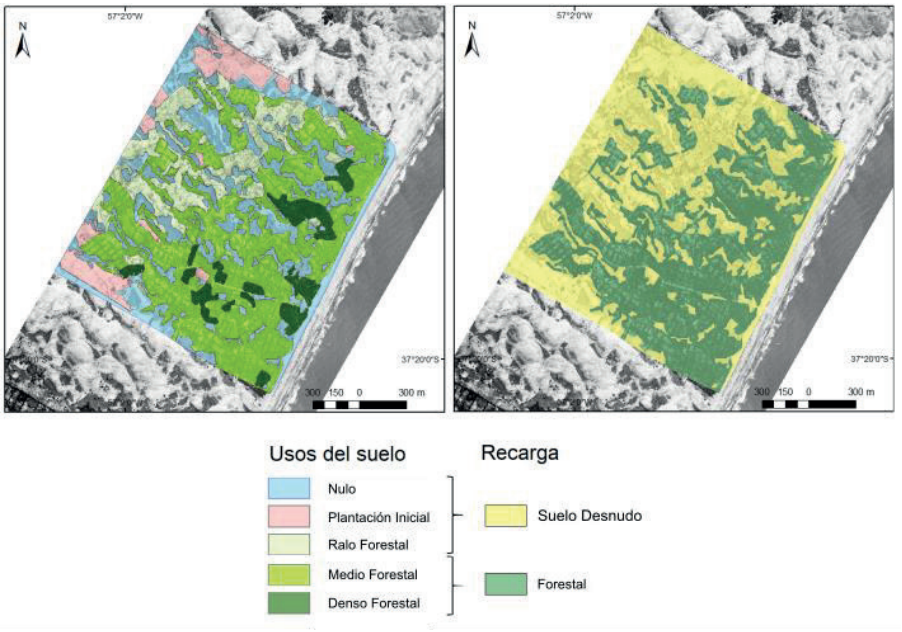

Fig. 3. Categorías de uso del suelo, y sus equivalentes según un criterio de recarga.

Finalmente, se calculó el volumen de agua que habría ingresado como recarga al sistema en las zonas de suelo desnudo y forestal, mediante la multiplicación de su extensión superficial en cada año por el promedio anual de excesos definido para cada zona. El valor total de recarga para cada año surge de la suma de los volúmenes de recarga correspondientes a cada zona. Esto permitió evaluar la variación en la recarga para el período considerado.

3 Resultados

3.1 Evolución del Uso del Suelo

La distribución de zonas de relieve definida en la fotografía de 1975 muestra que, de los 2,77 km^2 comprendidos en el área de mapeo, 81,7% corresponde a dunas costeras, y 18,3% a interdunas.

Se observan diferencias en la superficie ocupada por cada clase de uso del suelo en los dos momentos considerados (Fig. 4 y Fig. 5a). La Tabla 1 expresa dichas superficies en metros cuadrados.

El año 1975 representa una etapa inicial del proceso de forestación y amanzanamiento. Es por ello que una parte importante de la superficie corresponde al uso nulo (23,6%) y se observa la presencia de la categoría plantación inicial, con un 7,4% del total de la superficie mapeada. La categoría mejor representada es medio forestal, con un 45,8%, mientras que denso forestal se ubica en último lugar con un 6,8%.

En el año 2014 la superficie mapeada se encuentra ampliamente dominada por la categoría denso forestal (con un 83,0% de cobertura), mientras que medio y ralo forestal ocupan un lugar accesorio en la distribución territorial. Las zonas de uso nulo y plantación inicial han desaparecido por completo.

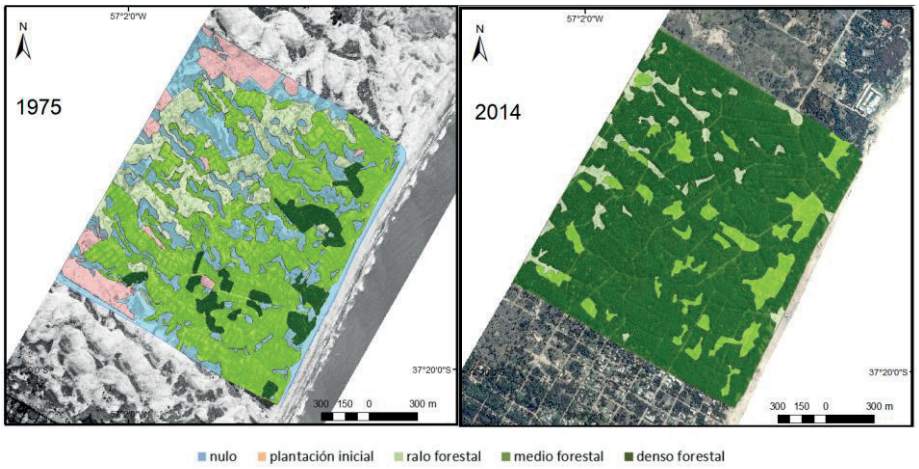

Fig. 4. Uso del suelo para 1975 y 2014.

Tabla 1. Usos del suelo en los años 1975 y 2014

	Área (%)	
Categoría	**1975**	**2014**
nulo	25,8	0,0
plantación inicial	7,5	0,0
ralo forestal	14,2	5,7
medio forestal	45,6	11,3
denso forestal	6,9	83,0
total	100	100

Las imágenes analizadas muestran el desarrollo de la forestación a lo largo de 39 años. Los cambios en la representación de las distintas categorías de uso del suelo indican un efectivo proceso de forestación, dado que, hacia el final del período, gran parte de la localidad se encuentra cubierta por un bosque bien desarrollado. Esto implica cambios en la disposición original de las superficies forestales, que debían ubicarse en las dunas costeras, no en las zonas de interduna. En 1975, el 96,0% de las áreas de interduna presentan un uso nulo, sin embargo, en 2014 la forestación ha ocupado por completo las zonas de interduna, con un predominio de la clase denso forestal (62,9%) (Fig. 5b). Las áreas de dunas costeras se encuentran ya forestadas en 1975, con un 56,5% de su superficie cubierta por el uso medio forestal, y las otras cuatro clases de

uso ocupando el 43,5% restante. En 2014, el 87,4% de la superficie de dunas costeras se halla cubierta por el uso denso forestal (Fig. 5c).

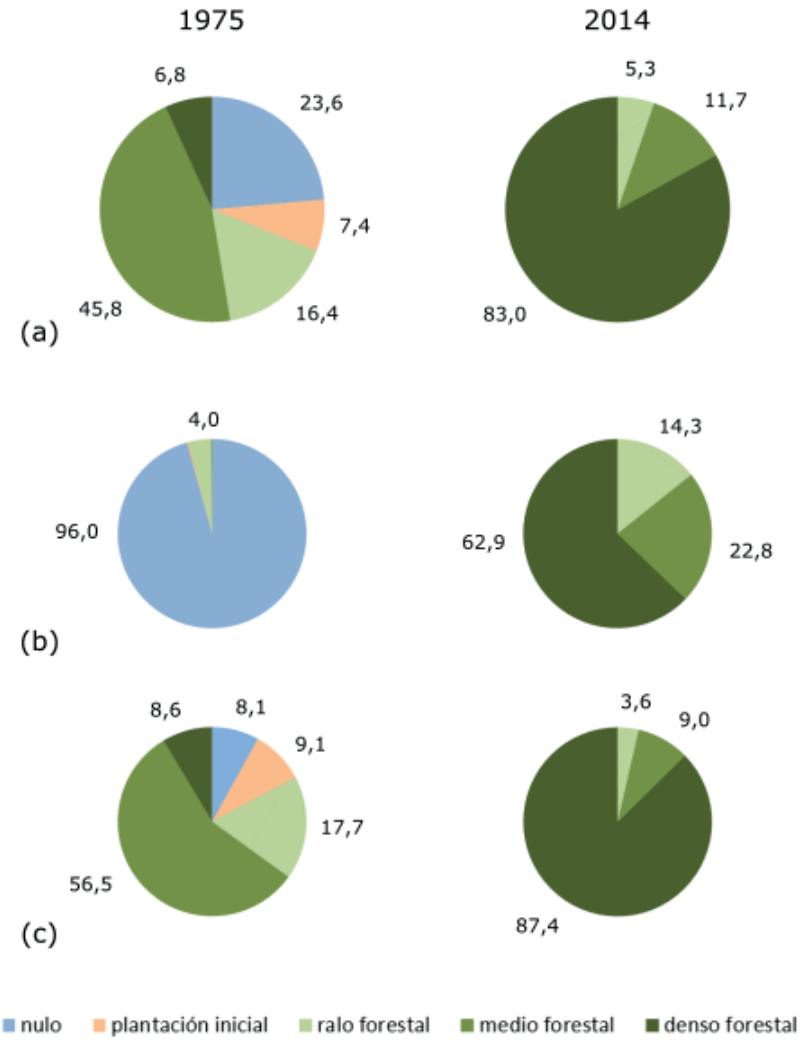

Fig. 5. Usos del suelo en 1975 y 2014, (a) en el área total de mapeo, (b) en las interdunas y (c) en las dunas costeras.

3.2 Evolución de las Superficies de Recarga

De acuerdo al criterio adoptado y la relación existente entre las clases de uso del suelo y las clases asignadas a la recarga, la Fig. 6 muestra la distribución de las superficies de recarga en 1975 y 2014.

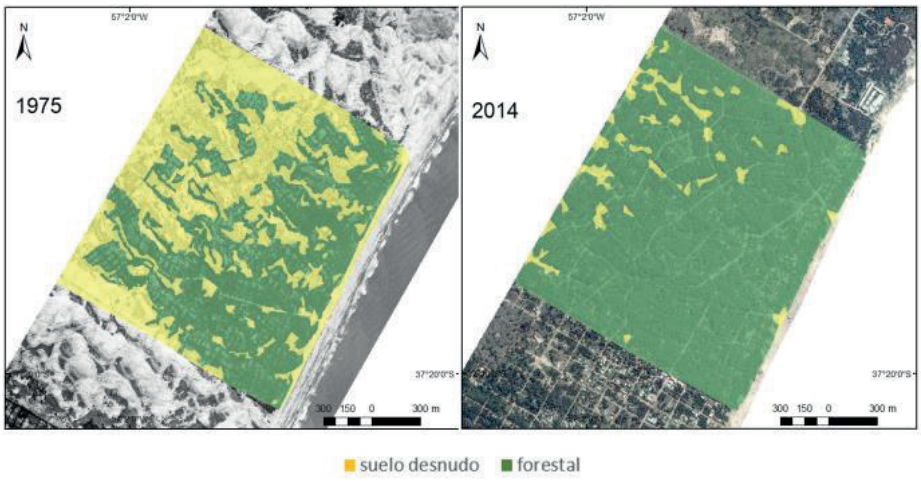

Fig. 6. Distribución de las superficies de recarga en 1975 y 2014.

En el año 1975, las clases suelo desnudo y forestal se encuentran casi igualmente representadas, con un 48 y un 52% de la superficie mapeada, respectivamente. En el año 2014, la clase forestal predomina ampliamente con un 94% de la superficie, mientras que la zona de suelo desnudo representa el 6% restante (Fig. 7).

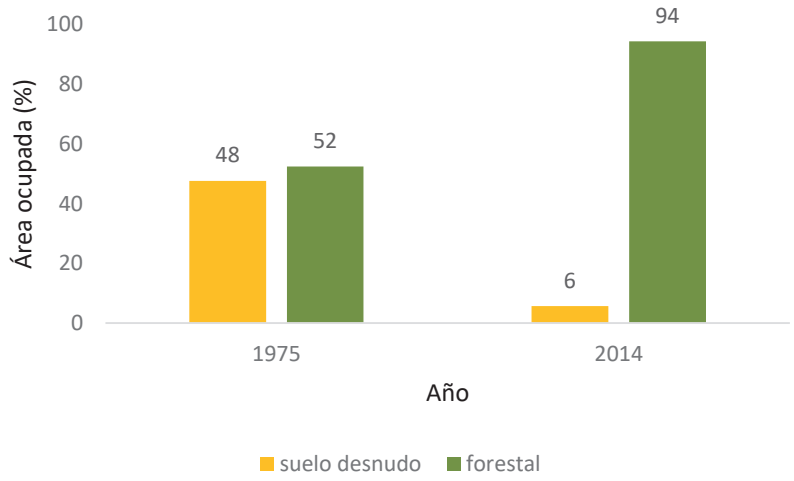

Fig. 7. Distribución porcentual de las clases de uso de suelo relacionadas a la recarga

Lo expuesto evidencia una clara tendencia a la expansión de la zona forestal, a expensas de la zona de suelo desnudo. Esto trae consecuencias sobre el ciclo hidrológico, dado que la capacidad de recarga asociada a la cobertura forestal es menor que la del suelo desnudo (Tabla 2).

Tabla 2. Datos promedio del balance hídrico para el periodo 1997-2016

		suelo desnudo			forestal		
Período	P[1] (mm)	ETP[2] (mm)	ETR[3] (mm)	Excesos (mm)	ETP (mm)	ETR (mm)	Excesos (mm)
1997-2016	930	669	506	422	912	711	223

[1]Precipitación, [2]Evapotranspiración Potencial,[3]Evapotranspiración Real

El promedio de precipitación anual es de 930 mm. Se aprecia casi el doble de excesos en la cobertura de suelo desnudo respecto de la forestal, con 422 mm y 223 mm anuales, respectivamente.

El volumen de agua que habría ingresado al sistema en el año 1975 es de 5,58 hm^3 en la zona de suelo desnudo y de 3,25 hm^3 en la zona forestal, lo cual suma una recarga total de 8,83 hm^3. Para el año 2014 la zona de suelo desnudo se encuentra drásticamente disminuida, y sólo aporta un volumen de 0,67 hm^3 a la recarga total, mientras que la zona forestal, ampliamente representada, presenta un volumen de recarga de 5,84 hm^3. La recarga total es de 6,51 hm^3, lo cual constituye una disminución del 26% respecto al valor de recarga de 1975 (Fig. 8).

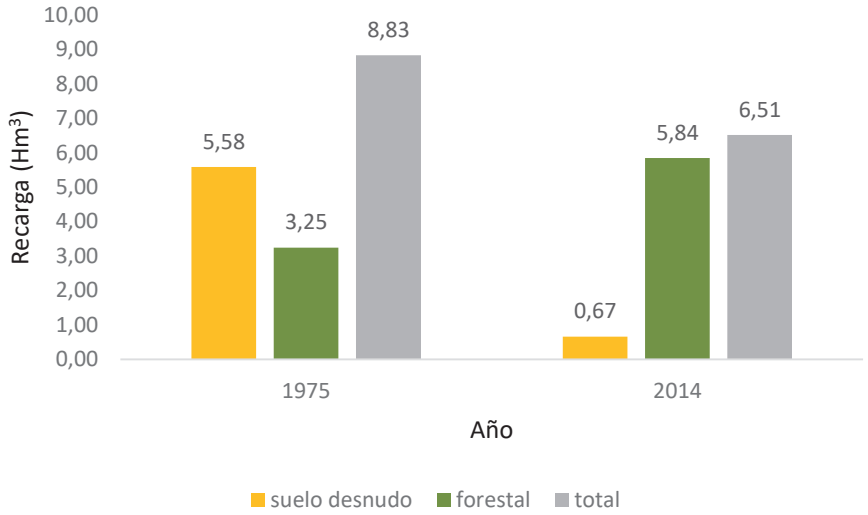

Fig. 8. Volumen de recarga para cada uso de suelo en los años estudiados

4 Conclusiones

Se realizó un análisis de la evolución de la cobertura del suelo en la localidad de Mar de las Pampas, Provincia de Buenos Aires, Argentina, entre los años 1975 y 2014.

Los resultados indican que las zonas forestales, inicialmente distribuidas en las dunas costeras, pasaron a ocupar las interdunas con el avance del tiempo. En 1975, casi la totalidad de las áreas de interduna correspondían a la clase de uso del suelo nulo, mientras que, en 2014, se encuentran enteramente cubiertas por forestación.

Considerando la superficie total de mapeo, la forestación muestra un claro aumento en su densidad a lo largo de la serie analizada. Entre los años 1975 y 2014, las clases de uso del suelo nulo y plantación inicial desaparecen, las clases ralo y medio forestal disminuyen su representación, y la clase denso forestal aumenta drásticamente, pasando de ocupar un 6,9% del área de mapeo en 1975, a un 83% de la misma en 2014.

En el año 1975, la forestación se hallaba en una etapa inicial y la superficie de recarga de suelo desnudo (compuesta por los usos nulo, plantación inicial y ralo forestal) ocupaba un 48% de la superficie. Sin embargo, la expansión del área forestada y el desarrollo de los árboles promovió la ocupación casi total de la zona por parte de la superficie de recarga forestal (categorías denso y medio forestal) para el año 2014. La disminución progresiva del área de suelo desnudo, que presenta un valor promedio de excesos de 422 mm, y el consecuente aumento del área forestal, con un promedio de excesos de 223 mm, modificó las condiciones hidrológicas superficiales de Mar de las Pampas. Se estimó que la recarga total en toda la superficie de la localidad varió de 8,83 hm^3 en 1975 a 6,51 hm^3 en 2014, lo cual representa una disminución del 26%.

Las diferencias en excesos de agua a causa de la forestación modifican significativamente la recarga en la localidad costera de Pinamar [21], que se ubica a pocos kilómetros y comparte características geomorfológicas y geohidrológicas con la zona de estudio. El presente estudio permite comprobar que la forestación también afecta la dinámica del agua subterránea en Mar de las Pampas, y produce una disminución de las reservas de agua dulce respecto de las condiciones originales del sistema. Mar de las Pampas aún no cuenta con cloacas, lo que puede ocasionar problemas de contaminación del acuífero por filtración de agua desde los pozos ciegos particulares. La combinación de este aspecto con las disminuciones en la recarga por causa de la expansión de la forestación, debe ser tenida en cuenta para lograr una planificación sustentable del recurso hídrico en la localidad.

La zona de estudio presenta un bosque de especies forestales exóticas (coníferas), originalmente instaurado con la finalidad de fijar las dunas para la construcción. Este bosque tiene, a su vez un valor paisajístico que actualmente es explotado, debido a la naturaleza turística de la localidad. Por otro lado, el presente trabajo demuestra el impacto negativo de la implantación de este bosque sobre la recarga del acuífero costero, en una zona donde el recurso hídrico subterráneo es limitado. Si bien se reconoce la importancia que actualmente reviste el bosque de coníferas para usos recreativos, el cuidado del agua subterránea debe ser incluido como prioridad a la hora de considerar la calidad ambiental de la zona. Se recomienda evitar la expansión de las coníferas en zonas donde aún no predominen, y en el caso de futuras expansiones de la zona forestada, recurrir a especies autóctonas para la fijación de dunas.

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Energy optimization for the operation of a sawmill

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Abstract. The wood drying is an important stage in the production process of a sawmill since it is where lumber acquires the level of humidity required by the market. Generally, it is a batch process that is carried out in dryers that operate in parallel out of phase. To cover the energy needs of the process, boilers fed with the by-products generated in the productive stages of the sawmill are used. To operate efficiently, the filling and scheduling of the dryers and the boiler feed and operation must be planned simultaneously. In this paper, these decisions are addressed through a mixed integer linear programming model (MILP) using state-task network concepts based on a discrete time formulation. Different work criteria related to sawmill operation are analysed, achieving very significant results for the performance of this industry.

Keywords: Drying Kilns, Sawmills, State-Task Network, Planning, Scheduling, MILP Model.

1 Introduction

The forest industry plays an important economic, environmental and social role in the development of the northeast region of Argentina. In this region there are more than 85% of the forest plantations for industrial purposes in the country and it is made up of more than 1,000 factories, of which sawmills represent 95% and, therefore, lumber production becomes a fundamental pillar of this industry.

The process in the sawmills consists of several production stages, where one of the most important is the drying. In this stage, the boards acquire the characteristics required by the market, increasing the value and quality of the wood. Usually, this stage is a batch process that is carried out in dryers or drying kilns, which may have different characteristics. To heat these furnaces, boilers are employed that mainly use the by-products generated in the activities of the sawmill as fuel (bark, sawdust, wood shavings and chip). With the steam generated, the air is heated by means of a heat exchanger and is forced to circulate through the dryers.

To carry out the planning of this stage, the filling and scheduling of the dryers must be simultaneously considered with the feeding and operation of the boilers. To achieve

even drying of the products in each drying cycle, each kiln must be filled with boards of the same thickness. The duration of each cycle depends on the thickness of the boards and the dimension of the kiln. Likewise, for each board thickness there is a set of drying programs that vary the cycle time and, consequently, the energy demand.

With the rise of the plants generating electricity from forest biomass, the by-products of the sawmills have increased in value, ceasing to be just a residue of the production that was used to feed the boilers. Therefore, the use of sawmill by-products must be appropriately planned in order to cover the energy needs and increase the processes profitability, avoiding the tradeoffs between both productions: lumber and electric power.

In the literature, few papers study the drying operation and most focus on improving the energy efficiency of the process or addressing the implementation of new technological alternatives such as solar dryers [1, 2]. To the best of our knowledge, only the work of Gaudreault et al. [3] approaches the planning of this operation through the development of two models: a mixed integer linear programming (MILP) and a constrained programming. Both approaches minimize the delay of product delivery, determining the batch allocation to each kiln and the operating times, but they do not take into account energy requirements for drying.

The planning of the drying stage can be classified as a programming problem of non-identical parallel units, and has been the subject of several studies [4, 5]. For the approach presented in this work, a State-Task Network (STN) formulation based on discrete times was chosen, since it allows a better control of the resources involved in the process [6, 7]. STN formulation was introduced by Kondili et al. [8], and in Castro et al. [9] a description of its application in different scheduling problems is presented. This approach has proven to be very effective in tackling this problem because it has allowed a very complex problem to be represented in a simple way.

In this work a MILP model is presented for the optimal planning of the drying stage in a sawmill for a given time horizon, where all involved decisions are made simultaneously. In this way, an adequate drying plan is obtained according to the availability of boards to be dried, by-products to cover the energy demand and the production policies of the firm, assessing all the involved trade-offs.

2 Problem Description

The drying of the wood is an intermediate stage in the production process of the sawmills. Its correct planning avoids the accumulation of wet boards generated in the previous stage and delivers boards with the required humidity levels to the next stage. (Fig. 1).

Boards enter this stage with the objective of reducing their humidity level to comply with market requirements. These boards are grouped according to their thickness and put together with the inventory of non-dry boards, which are waiting to be dried. The frequency in which the boards arrive at this stage depends on the production in the previous stage of sawing.

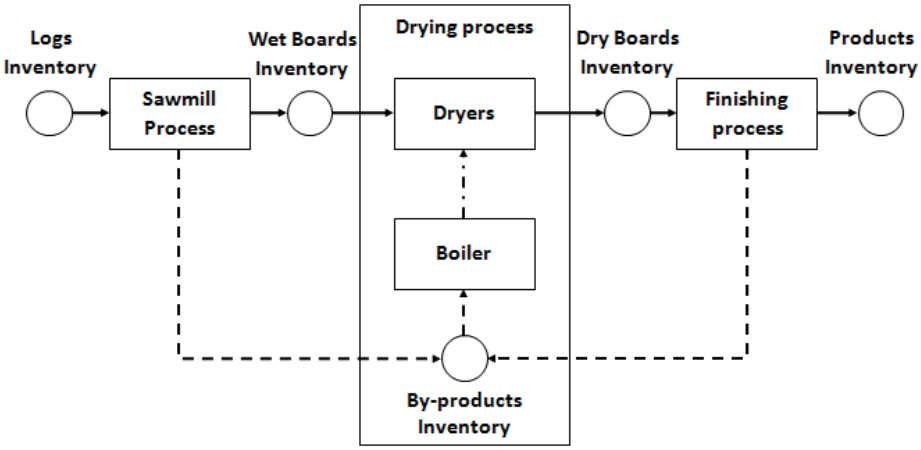

Fig. 1. Stages of a drying program

The sawmill has a set of drying kilns that do not necessarily have the same dimensions. When the dryer is loaded, it begins a drying cycle. To ensure even drying, each drying cycle must contain boards of a single thickness. On the other hand, to guarantee the efficient use of the dryers, a minimum load is established for each kiln. The duration of each cycle varies according to the size of the kiln and the thickness of the boards to be dried. At the same time, for each board thickness there is a set of drying programs with a different duration of the drying cycle and, consequently, a different energy demand. Each drying program considers three stages: kiln heating, drying, and cooling (Fig. 2). In addition, there is a setup time between each drying cycle, which depends on each dryer and corresponds to its filling.

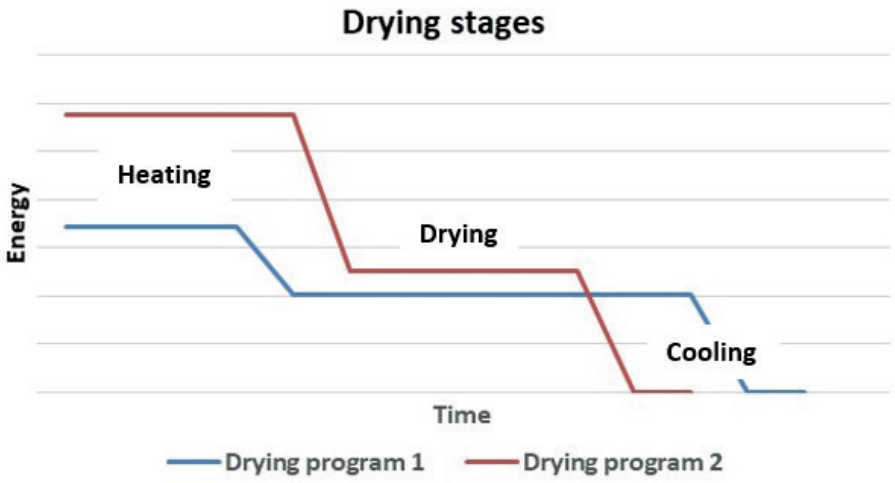

Fig. 2. Stages of a drying program

In order to cover energy requirements, a solid fuel boiler fed with by-products generated in the activities of the factory is used. For a correct operation of the boiler, the supply must fulfil certain proportion requirements between the various by-products to ensure humidity levels, volatility and ash generation in combustion. Just like boards, according to the sawing stage, by-products are available in the inventory for being used as fuel.

The objective of the presented approach is to plan the drying operation during a time horizon, considering different planning criteria. Explicitly, the thickness of boards to be dried in each drying kiln, the programs to be selected, and the operating times for the different kilns are simultaneously determined through a MILP model according to diverse objective functions for the planning. In addition, the resources used to satisfy the energy requirement are selected.

3 Model formulation

The proposed formulation is based on an STN model that uses a discrete time grid. The time horizon is divided into discrete times t of equal duration, which are determined according to the drying operation times and the regularity in the delivery of boards. In the STN, states are represented through index e and represent the thickness of the boards to be dried. The drying task is implemented according to program p in dryer d. As resources for the drying of boards, the by-products generated in the productive stages of the sawmill are considered as types of fuel b, and are used to cover the energy requirements of the drying (Fig. 1).

Let x_{dtep} be the binary variable that determines the beginning of a drying cycle in dryer d in time t using program p for boards of thickness e. Each drying program p is characterized by its duration (Tp_{dep}) and its energy requirement, taking into account kiln d being used and board thickness e. Also, energy consumption is determined according to the different phases explained in Fig. 1. It is estimated through parameter $ES_{dt'ep}$ that indicates the energy required in the period between times t' and t'+1, again taking into account the selected program p, board thickness e and dryer d being used when the drying cycle has started at time t, i.e. x_{dtep} equal 1.

Eq.(1) states that at most one single drying program p can be started in dryer d at each time t. This expression takes into account the duration of drying program p for boards of thickness e in dryer d (Tp_{dep}) and the setup time of the kiln (Ts_d).

$$\sum_{t'}^{t=t+Tp_{dep}+Ts_d-1} \sum_e \sum_p x_{dt'ep} \leq 1 \qquad \forall\, d, t \tag{1}$$

Let NE_{te} be the quantity of boards of thickness e that enter the drying stage in time t. These boards are added to the inventory of non-dried boards with the same thickness from the previous time ($I_{t-1,e}$). Eq.(2) states the material balance at time t, which establishes that the boards in stock at time t-1 plus the ones that enter at time t must be equal to the boards to be dried plus the remaining ones kept in inventory. Qp_{dte} represents the quantity of boards of thickness e that enter dryer d at time t.

$$I_{t-1,e} + NE_{te} = I_{te} + \sum_d Qp_{dte} \qquad \forall t > 1, e \tag{2}$$

For a correct operation, the load of the dryers is between minimum and maximum values ($CMin_d$ and $CMax_d$, respectively) established by the company while taking into account the capacity and technology of dryers (Eq.(3)).

$$CMin_d \sum_p x_{dtep} \leq Qp_{dte} \leq CMax_d \sum_p x_{dtep} \qquad \forall\, d, t, e \tag{3}$$

Eq.(4) determines the energy required by each dryer at time t (ER_{dt}). This expression considers the different stages if a drying cycle has started and takes into account consumption between times t and t+1.

$$ER_{dt} = \sum_e \sum_p \sum_{t'=0}^{Tp_{dep}-1} ES_{d(t')ep}\ x_{d(t-t')ep} \qquad \forall\, d, t < t' \tag{4}$$

The total energy required by dryers at time t cannot exceed the maximum energy that can be provided by the boiler ($EMax$) and must exceed a minimum value ($EMin$) for its proper operation (Eq.(5)).

$$EMin \leq \sum_d ER_{dt} \leq EMax \qquad \forall\, t \tag{5}$$

Eq.(6) determines the types of fuel b used by the boiler to cover the required energy.

$$\sum_d ER_{dt} = f \sum_b Qb_{tb} cp_b \qquad \forall\, t \tag{6}$$

where Qb_{tb} is the amount of fuel b consumed by the boiler in time t, cp_b is the calorific value of fuel b, and f is a factor of boiler efficiency.

Eq. 7 determines the total amount of fuel (Tb_t) used at each time t.

$$Tb_t = \sum_b Qb_{tb} \qquad \forall\, t \tag{7}$$

Fuel b being used at time t must not exceed a percentage (fb_b) of the total amount (Tb_t) being used in order to assure the proper functioning of the boiler (Eq.(8)).

$$Qb_{tb} \leq fb_b\, Tb_t \qquad \forall\, t, b \tag{8}$$

The availability of fuel b is determined according to Eq.(9), where IB_{tb} represents the inventory of fuel b at time t and NB_{tb} is the amount of fuel b that arrives at time t from sawmill activities for the boiler.

$$IB_{t-1,b} + NB_{tb} = IB_{tb} + Qb_{tb} \qquad \forall t, b \tag{9}$$

The operating criteria in the drying stage can vary according to both the level of production of sawmills and the policy adopted by the firm. These criteria can be contrasted among them, and this analysis is really interesting. Next, different objectives are posed.

3.1 Objective function 1 (FO 1): Maximization of the quantity of dried boards

This criterion tries to dry as many boards as possible over the time horizon. It is a widely used measure, but it loses sight of the costs generated in the process.

$$max\ FO\ 1 = \sum_d \sum_t \sum_e Qp_{dte} \tag{10}$$

3.2 Objective function 2 (FO 2): Costs minimization

The second criterion (Eq.(11)) minimizes costs due to the use of the drying kilns (*Cd*) and the cost of fuel consumption (*Cf*).

$$min\ \ FO\ 2 = Cd + Cf \tag{11}$$

Cd cost represents a fixed cost for each performed drying cycle, which depends on the dryer being used, the thickness of the boards to be dried, and the selected drying program ($Cdry_{dep}$). It is calculated as follows:

$$Cd = \sum_d \sum_t \sum_e \sum_p Cdry_{dep} x_{dtep} \tag{12}$$

Cf cost is obtained from the Eq.(13), where Cb_b is the unit cost of fuel *b*.

$$Cf = \sum_t \sum_b Cb_b Qb_{tb} \tag{13}$$

Furthermore, in order to assure a minimum quantity of dried boards, the inventory of boards by the end of the planning horizon must not exceed a certain percentage *fp* of the total available boards through the planning horizon (*Te*) (Eq.(14)). *Te* is defined as the sum of the tables that were in inventory at the beginning of the horizon and those that enter the drying stage (Eq.(15)). Another different and admissible approach is to set conditions for each board thickness instead of using a global condition. The following expression is used in this work:

$$I_{t=|T|,e} \leq fp\ Te \tag{14}$$

$$Te = fp\ \sum_e \left(I_{t=0,e} + \sum_t NE_{te}\right) \tag{15}$$

3.3 Objective function 3 (FO 3): Makespan minimization

The aim of this objective function is to dry the highest number of boards as soon as possible.

$$min\ FO\ 3 = MK \tag{16}$$

where *MK* corresponds to the end time of the last planned drying cycle in the time horizon, which is calculated in Eq.(17).

$$MK \geq\ ord(t) x_{dtep} + \left(Tp_{dep}\ + Ts_d\right) x_{dtep} \tag{17}$$

where ord(*t*) corresponds to the position in which time *t* is in the set. In this case, a requirement is added on the minimum of boards to be dried such as Eq.(14-15).

4 Examples

In order to evaluate the performance of the proposed model, an example corresponding to a sawmill with 4 dryers is presented and two cases with different availability of fuel will be analysed. In Case I, there is limited availability, while in Case II, availability is enough to meet any required demand. Table 1 shows the capacity of each dryer.

Table 1. Dryer capacity [*tn*]

Dryer	*CMin*	*CMax*
d_1-d_2	45	60
d_3-d_4	75	100

Note: tn, tons

At the beginning of the planning, two kilns are busy with drying cycles from the previous planning. The drying cycles of this plan must begin before time $t = 60$. At the beginning of the planning horizon, the inventory of tables and fuel is null ($I_{t=0,e}$=0 and $IB_{t=0,b}$ =0, respectively) and the boards are classified in 3 thicknesses which each one has 3 drying programs. Table 2 displays the duration of each drying cycle according to the dryer, thickness of boards and drying program, and the kilns setup time required for each dryer. Table 3 shows the fixed cost for each drying program, while Table 4 presents the costs for fuels and their calorific value.

Table 2. Processing times

Dryer	Board thickness	Drying program			Setup time
		p_1	p_2	p_3	
d_1-d_2	e_1	13	10	8	1
	e_2	18	14	11	
	e_3	23	21	17	
d_3-d_4	e_1	22	18	14	2
	e_2	30	23	19	
	e_3	39	30	24	

Table 3. Drying program cost [*$*]

Dryer	*Board thickness*	*Drying program*		
		p1	*p2*	*p3*
d_1-d_2	e_1	43.9	33.8	27.0
	e_2	56.3	43.8	34.4
	e_3	58.8	53.7	43.5
d_3-d_4	e_1	58.8	48.1	37.4
	e_2	74.0	56.7	46.9
	e_3	76.1	58.5	46.8

Table 4. Fuel parameters

Fuel	Costs [*$/tn*]	Calorific value [*MJ/tn*]	Boiler feed [*%*]
Bark	2.39	5998.22	15
Chip	5.33	7117.39	100
Wood shavings	4.02	16486.45	20
Sawdust	3.39	6363.77	15

Note: tn, tons; MJ, mega joules

Table 5 and 6 indicate the quantity of boards and fuel that enter the drying stage throughout the studied horizon, respectively.

Table 5. Quantity of boards that enters drying stage in each time [*tn*]

Board thickness	Time				
	t_0	t_{12}	t_{24}	t_{36}	t_{48}
e_1	30	130	190	60	10
e_2	170	170	170	80	50
e_3	150	50	160	0	20

Note: tn, tons

Table 6. Fuel entering each time in Case I [*tn*]

Fuel	Time				
	t_0	t_{12}	t_{24}	t_{36}	t_{48}
Bark	15	9	8	11	12
Chip	169	107	91	127	140
Sawdust	84	53	45	63	70
Wood shavings	25	16	13	19	21

Note: tn, tons

In this example, the boiler can deliver up to 150000 MJ/h, but, at the beginning of the time horizon, a fraction of this power is reserved to cover the energy required by the previous drying plan. The example is implemented and solved in GAMS using CPLEX solver in an Intel(R) Core(TM) i7-3770, 3.40 GHz. The computational time limit is fixed to 3600 CPU sec. The model consists of 10834 equations, 8061 continuous and 2043 binary variables.

The global results are shown in Table 7. The value obtained for each objective function is highlighted in each column. For FO 2, the maximum allowed level for boards inventory at the end of the planning horizon (*fp*) varies from 25% to 5% of the available boards for drying. This is done in order to analyse different planning scenarios and the impact of the final inventory level when cost is minimized. Also, in order to carry out

appropriate comparisons, it is required for FO 3 to keep the same stock as the solution obtained with FO 1. The last 3 columns of the table correspond to Case II. For this case, only *fp* = 25% is analysed for FO 2. As it can be seen, optimal solutions are obtained with reasonable computing times in almost all cases, except when *fp* = 15%, which results in an optimality gap equal to 0.7.

Analysing FO 1 in Case I, 1,380 tons of boards are dried in 19 drying cycles, which end at time t = 100, leaving 4.2% of the total boards without drying in inventory. By not considering the costs within the objective function, the shortest programs are selected, with a higher consumption of fuel, which allow drying a greater number of boards.

With FO 2, as *fp* decreases, and with this the need to dry more boards at the same time, the number of drying cycles increases and simultaneously the use of the short drying program p3 tends to increase, generating higher fuel costs. Using FO 3, it is possible to dry the same as FO 1 but with lower cost and faster.

In Case II, the greater availability of fuel allows to improve the results of all objective functions. Using FO 1, the number of dried boards increases, but fails to dry the total, leaving 30 tons in inventory for the next planning. With FO 2 for *fp* = 25% the cost is decreased by 1.1%, and FO 3 shows a reduction of 17 units of time in manufacturing, but with a 40.7% increase in costs, with respect to the same objective function of Case I.

Table 7. Results of Example

	Case I							Case II		
		FO 2 Maximum inventory of board (*fp*)								
	FO 1	**25%**	**20%**	**15%**	**10%**	**5%**	**FO 3**	**FO 1**	**FO 2**	**FO 3**
Drying cost [*$*]	814.9	805.7	794.1	826.1	821	820.1	820.1	759	805.7	747.2
Fuel cost [*$*]	4345.1	2012.2	2551.6	3049.6	3574.7	4288.5	4306	6445.5	1980.5	6466.5
Total cost [*$*]	5160	**2817.9**	**3345.7**	**3875.8**	**4395.7**	**5108.6**	5126.1	7204.5	**2786.2**	7213.7
Dried boards[*tn*]	**1380**	1080	1160	1240	1300	1380	1380	**1410**	1080	1410
Final inventory [*tn*]	60	360	280	200	140	60	60	30	360	30
Inventory [*%*]	4.2	25	19.4	13.9	9.7	4.2	4.2	2.1	25	2.1
Performed programs										
Drying program 1	3	12	7	7	5	4	4	1	12	1
Drying program 2	5	2	9	7	7	4	4	1	2	1
Drying program 3	11	0	0	2	5	11	11	17	0	17
Total drying cycles	19	14	16	16	17	19	19	19	14	19
Total consumed fuel [*tn*]										
Bark	55	55	55	55	55	55	55	2.8	68.5	2.8
Chip	634	240.8	329.7	413.9	502.7	623.5	634	1204.5	228.4	1208.5
Sawdust	136.4	68.3	84.5	99.3	115	136.3	124.5	0	68.5	0
Wood shavings	94	91	94	94	94	94	94	3.8	91.4	3.8
Makespan [*t*]	100	91	90	91	100	100	**98**	88	90	**81**
CPU Time [*sec*]	142	2	383	3610	161	287	383	20	4	81
gap [*%*]	0	0	0	0.7	0	0	0	0	0	0

Note: tn, tons

Fig. 3 shows the Gantt charts, depicting in red the drying cycles performed for boards of thickness e_1, in green those of thickness e_2 and in blue the corresponding to thickness e_3. The blocks with squares correspond to drying programs p_1; those with oblique lines are cycles with drying program p_2; and those in solid colour correspond to drying program p_3. The drying cycles from a previous drying plan are displayed in grey. For FO 2, only the planning for the case considering fp = 25% is shown.

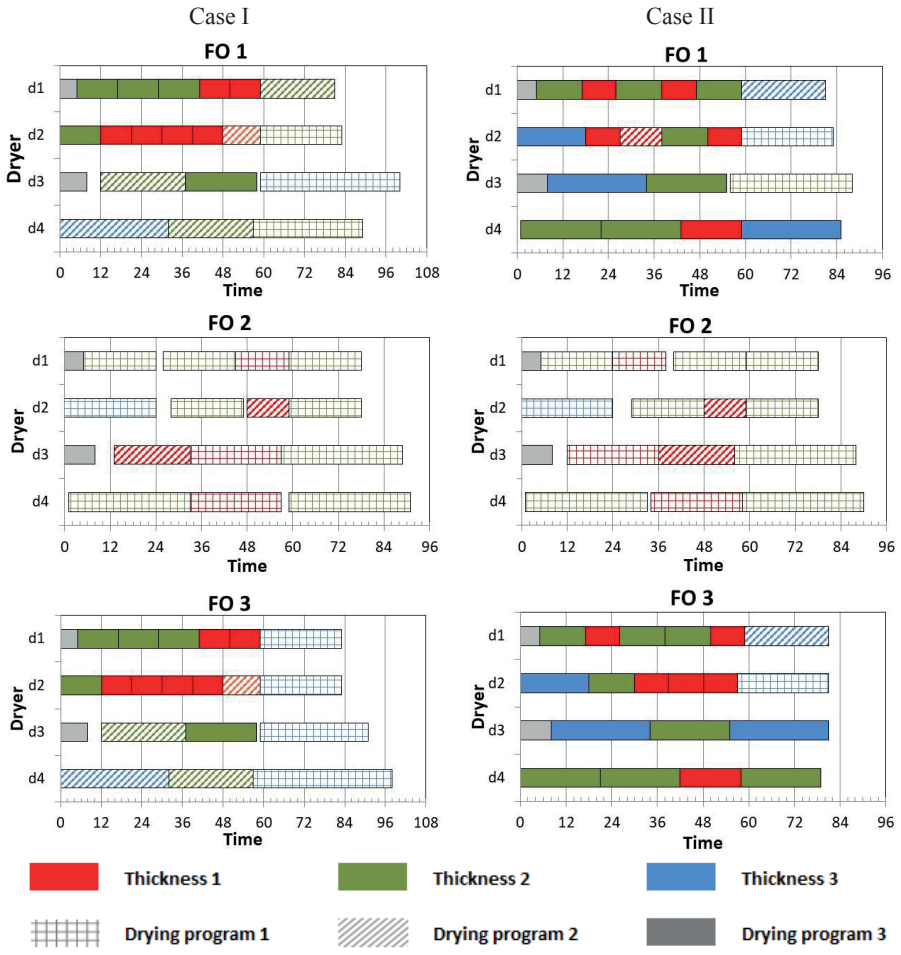

Fig. 3. Gantt chart of the drying plan

It can be seen in Fig. 3 that in FO 2, the dryers have the amount of chip a greater number of idle times, due to the low number of drying cycles. In FO 3 of Case I, the lack of fuel forces to select slower drying programs, preventing a significant reduction in the time of completion of the drying plan if compared to FO 1. This can be better understood by looking at Fig. 4a, which represents the consumption and inventory of each fuel over the horizon. Although at the end of the horizon even sawdust is available

(the only one in stock), it is not allowed to feed the boiler only with this fuel since the boiler does not work correctly (Eq. (7)).

Fig. 4b depicts the percentage of the type of fuel used to feed the boiler. Depending to the limit value of each fuel (fb_b), the amount of chips used at any given time is greater than 50% and, in some cases, corresponds to 100% of the boiler supply. Fig. 5 shows the energy generated by the boiler to cover the energy demand during the time horizon and the maximum limit it can generate. As it can be seen, at the beginning, the maximum limit of the boiler is reduced because the difference is reserved for the energy requirement of the previous drying plan.

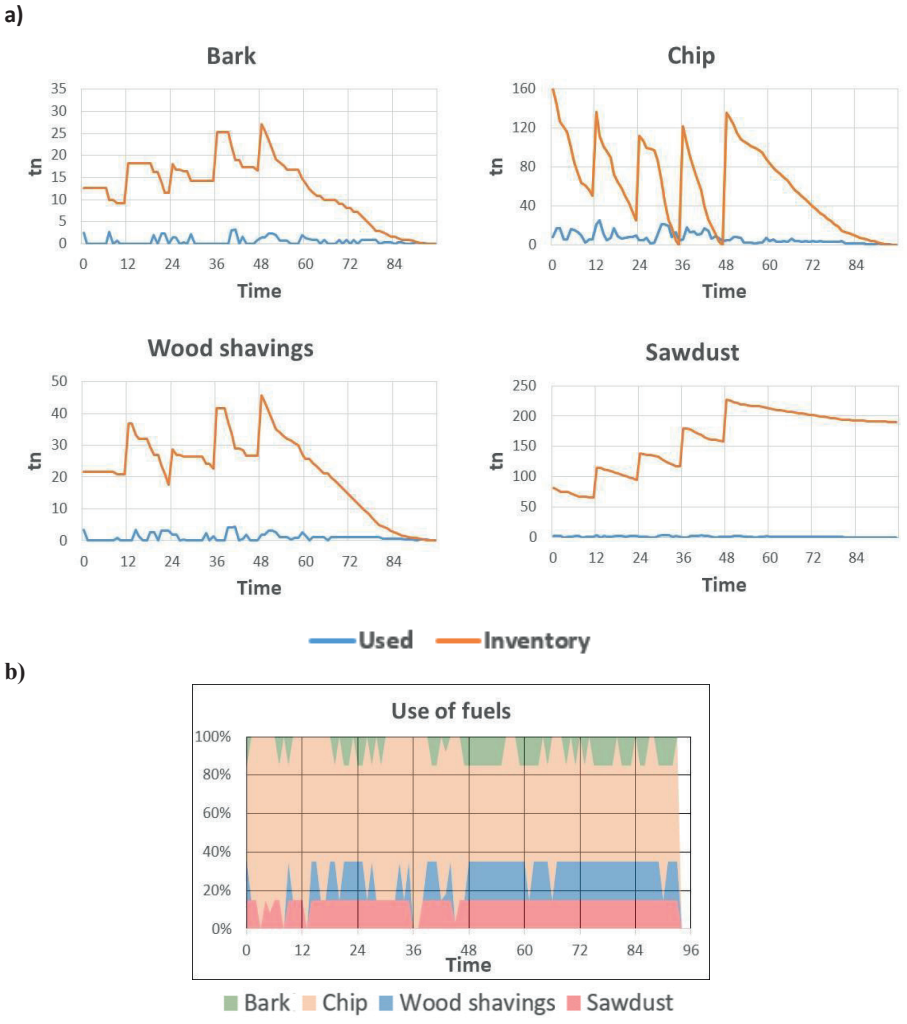

Fig. 4. Use of fuel for FO 3 of Case I

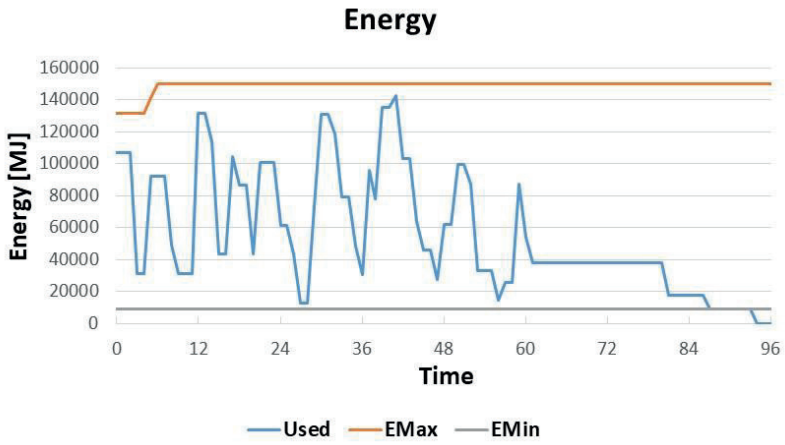

Fig. 5. Energy provided by the boiler for FO 3 of Case I

4.1 Comparative analysis and discussion of results

By comparing the obtained results, different drying plans are reached according to the considered objective function. Although FO 1 is usually more common in the forest industry when planning is addressed, many times with more heuristic tools or approaches, the presented approach allows evaluating different drying process scenarios. In this way, new perspectives are opened for companies in the sector in relation to the optimal management of the drying operation. This is reinforced if new options for the use of by-products, based on the use of biomass, are considered in the analysis. In this section, a discussion of the different criteria considered and the trade-offs between them is presented.

For FO 1, a greater number of boards are dried using a greater number of drying cycles. By not considering costs in this objective function, shorter drying programs are used, with higher energy consumption, generating the highest total costs. With FO 2, it is observed that the number of dry boards and drying cycles increases as *fp* decreases, using longer drying programs with less energy and fuel consumption, and consequently lower cost. As expected, when considering FO 3, the drying plan is carried out in less time, using a number of cycles similar to that of FO 1 but the downtimes between cycles decrease. By-product availability is an important factor in the planning, as can be glimpsed in Case I. All the objectives functions are improved when greater amount of fuel is available. However, the new possibilities to take advantage of these resources generate scenarios that this formulation can help to analyse.

Finally, the trade-offs between the different criteria considered are analysed. Obviously, generating an objective function that incorporates these 3 criteria would allow an adequate evaluation to be carried out. However, this is not possible as these criteria are expressed in different units (product, money and time). In the case of FO 1, the

value contributed in the drying operation could be weighed when the wet boards are transformed into dry boards, but as in reality the wet boards lack commercial value, it is an abstraction that is very difficult to be specified. Therefore, a more appropriate strategy to plan the operation is to incorporate restrictions that involve the criteria considered. In the previous example, this strategy has been implemented establishing conditions on the production level through restrictions on the final inventory of undried boards.

In the case of FO 2, which minimizes costs, the drying plan has been analysed by varying the final inventory of undried boards. The conditions on the time horizon could have been added using Eq. 17 and incorporating a limit for makespan. Similarly, in FO 3, MK is minimized and production limitations were considered. Here you could add restrictions to limit the cost of operation. In short, the formulation admits the combination of the different criteria, which enhances its capacity for analysis and evaluation. Given the difficulty of including the criteria in a single expression as an objective function, the best alternative is to incorporate them through restrictions in the formulation.

Therefore, evaluating and adjusting these criteria can guide planners to make a good decision to analyze the wood drying process.

5 Conclusions

A MILP model with a State-Task Network formulation based on discrete times was presented for optimal planning of the drying stage of a sawmill over a time horizon. This allows to simultaneously determine the type and quantity of boards to dry, the selected drying program and the start time, together with the energy required and how this requirement is covered with the use of fuels. Three objective functions were presented. Although FO 1 is generally more common in the forestry industry, the presented approach allows evaluating different drying process scenarios. Comparing the results obtained, different drying plans are reached according to the objective function considered, in reasonable CPU times.

Finally, the proposed approach is a useful tool for planning the drying stage of sawmills, allowing efficient use of available resources.

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A column generation based algorithm for solving the log transportation problem

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Abstract. In this work, a solution approach based on column generation for the log transportation problem in the Argentine forest industry is presented. This problem involves making decisions that covers aspects related to the size of the truck fleet, different types of delivered raw materials, different regional bases where trucks begin and end the routes, legal and contractual restrictions, among others, generating a problem very difficult to solve. This work is focused on the determination of the routes to be performed by the truck fleet to supply the plants with the available raw materials in the forest sites, at minimum cost. A representative case study of the Argentine forestry sector is presented and the corresponding results are detailed. The proposed approach allows solving problems with more than 500 full truck loads to transport per day (approximately 13,500 tons of raw materials) in less than 15 minutes of execution and with a negligible optimality gap.

Keywords: Transportation Planning, Forest Industry, Column Generation.

1 Introduction

According to the Ministry of Agroindustry [1], the industrial forest region of northeast Argentina (involving the provinces of Entre Ríos, Corrientes and Misiones) encompasses 766 production plants, which represents 37% of the country's forestry companies. Of this total, 42% corresponds to micro-companies (annual production level less than 940 m^3), 39% corresponds to small companies (between 940 and 4,720 m^3), 17% corresponds to medium companies (between 4,720 and 23,585 m^3), and the remaining 2% corresponds to large companies (annual production level greater than 23,585 m^3). Regarding the level of employment, this region generates direct employment for 12,332 people, 50% of whom are in the province of Misiones. The province of Misiones is the main consumer and producer of logs: 61% of the raw material (logs) was obtained in this province (more than 2 million tons per year) in the last census year [2]. The log extraction level in Misiones was 5,914,877 m^3 (4,731,902 tons) during the last census year, which is equivalent to 172,069 full truckloads to transport per year (550 full truckloads per day, approximately). Since log transportation is a very expensive activity, significant savings can be obtained through efficient transportation planning.

In this work, the distribution of logs from the harvest areas to the plants is addressed. This problem involves complex decisions, where the truck fleet size and the raw materials supply are the typical ones. There are several aspects to be considered, such as legal and contractual restrictions (time spent on the road, number of allowed daily trips, among others), that make the problem complex and difficult to be solved. The log transportation problem tackled in this work involves decisions related to: supply allocation (assignment of raw material from harvest areas to plants), truck routing (assignment of trips to trucks and the order in which they are made), and the size of the truck fleet (the number of trucks that are used to satisfy plants requirements). Many times scheduling decisions (determination of specific times for each truck activity) are also considered, but this is beyond the scope of this work. Taking into account the involved decisions, integrated formulations are required, which enlarges the model size and hinder the resolution. In this way, developing a tool capable of solving the problem efficiently and in a reasonable computing time is relevant for this industry.

However, there are few works presented in the literature that jointly address the allocation and routing problems. In fact, regardless of the methodology adopted, they resort to decomposition approaches in order to simplify problem resolution. Trips are assumed to be known in advance or are generated prior to the trucks routes determination; that is, first, the supply of each harvest area to each plant is determined (allocation problem) and, subsequently, the routes of each vehicle are generated (routing problem) and scheduled (scheduling problem) taking into account the previously selected flows. Many times, allocation problem is solved from a tactical perspective, assuming that the solution will be effectively implemented through appropriate routing and scheduling formulations ([3], [4], [5]). However, from a strictly mathematical point of view, this decomposition approach does not guarantee to reach the optimal solution of the problem, although, from a productive perspective it allows to achieve appropriate solutions. In this sense, metaheuristics approaches have been also used to address some of the aforementioned problems ([6], [7]).

In a previous work, Bordón et al. [8] propose a mixed integer linear programming (MILP) model to solve a simplified version of the aforesaid problem, assuming that each plant demands a single type of raw material. This assumption is a strong simplification that significantly limits the application of the proposed approach, taking into account that different raw materials are employed and transported in this industry. Unlike such work, in this paper is assumed that different raw materials are required by each plant taking into account that diverse specific production requirements must be daily met. In this way, the supply of specific raw materials is another decision variable to be considered. These assumptions significantly increase the model complexity and the number of model variables.

In addition, for real-practice problems of this industry, the model size is large, with numerous trips and involved vehicles, and, then, computational performance worsens. Therefore, an adequate solution approach must be developed in order to achieve reasonable performance for the real problems of this industry. So, a Column Generation (CG) based approach is proposed in order to obtain an integer feasible (near optimal) solution in a short computing time. The works of Palmgrem et al. [9]

and Rix et al. [10] are outstanding antecedents in the use of this methodology to solve transportation problems in the forest industry, although they solve different problems to the one posed in this article (i.e., allocation is not taken into account but scheduling is considered).

Summarizing, the focus of this article is on the operational planning, specifically, on the simultaneous optimization of allocation and routing problems in order to deliver logs and forest raw materials from harvest areas to production plants, at minimum cost. The capabilities of the proposed methodologies are shown through an example from the Argentine forest industry.

In the following section, the addressed problem is stated. In sections 3 and 4 the proposed mathematical model and the CG-based approach are presented, respectively. In section 5 a case study is analyzed and, finally, in the last section, conclusions are exposed.

2 Problem statement

The problem addressed in this work considers a set F of harvest areas. At each harvest area f, there is available a number of full-truckloads of raw material m, $supply_{f,m}$, $m \in M$, used to supply a set of plants I, which demand a certain number of full-truckloads, $demand_{i,m}$, of raw material m.

To transport the raw materials (logs) from harvest areas to plants, a set of trucks C is available. Each truck c, $c \in C$, begins and finishes its route in a regional base p, $p \in P$. In addition, each truck c can perform a limited number of trips, and transport only one type of raw material m at a time. Also, each truck c has a maximum number of working hours, $maxt$.

The route representation proposed by Bordón et al. [8] is used in this work. Accordingly, each route is composed of a series of trips v, $v \in V$, where a trip v is a sequence of different movements. As can be seen in Fig. 1, the first two types of trips are made up by three movements, two unloaded (dashed lines) and another loaded (solid lines), meanwhile the two remaining are conformed by two movements, one unloaded and another loaded. Therefore, according to the above trip definition, the proposed approach assembles the routes through trips composition which are simultaneously assigned to the truck in the overall model, using binary variables, one for each type of movement.

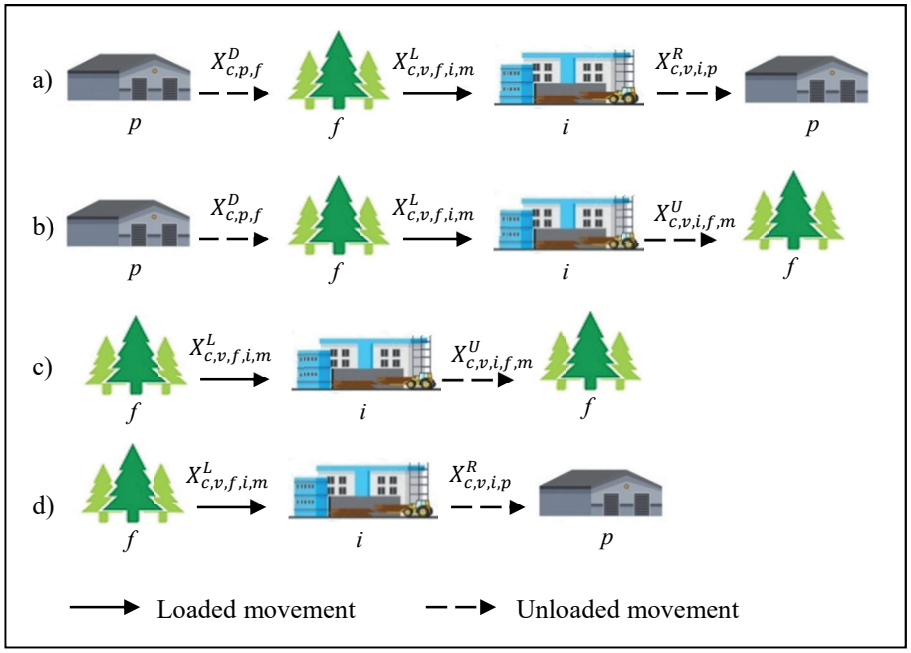

Fig. 1. Trips composition

Thus, the objective of the present work is the minimization of the total transportation costs, subject to demand fulfillment and legal and contractual restrictions.

3 Mathematical model

In this section the proposed mathematical model (P1) is presented. Note that the parameters are written in lower case, while the variables are written in upper case.

$$\min Z = \sum_{p\in P}\sum_{c\in C_p}\sum_{f\in F} cd_{p,f}\, dpf_{p,f}\, X^D_{c,p,f} +$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} cl_{f,i}\, dfi_{f,i}\, X^L_{c,v,f,i,m} +$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} cu_{i,f}\, dif_{i,f}\, X^U_{c,v,i,f,m} +$$

$$\sum_{p\in P}\sum_{c\in C_p}\sum_{v\in V}\sum_{i\in I} cr_{i,p}\, dip_{i,p}\, X^R_{c,v,i,p} + \sum_{p\in P}\sum_{c\in C_p}\sum_{f\in F} cfix\, X^D_{c,p,f} \quad (1)$$

Subject to:

$$\sum_{c\in C}\sum_{v\in V}\sum_{i\in I} X^L_{c,v,f,i,m} \le supply_{f,m} \quad f \in F,\ m \in M_i \quad (2)$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F} X^L_{c,v,f,i,m} \ge demand_{i,m} \quad i \in I,\ m \in M_i \quad (3)$$

$$\sum_{c}\sum_{v}\sum_{i}\sum_{m\in M_i} X^L_{c,v,f,i,m} = \sum_{c\in C}\sum_{p\in C_p} X^D_{c,p,f} +$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{i\in I}\sum_{m\in M_i} X^U_{c,v,i,f,m} \quad f \in F \tag{4}$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F}\sum_{m\in M_i} X^L_{c,v,f,i,m} = \sum_{p\in P}\sum_{c\in C_p}\sum_{v\in V} X^R_{c,v,i,p} +$$

$$\sum_{c\in C}\sum_{v\in V}\sum_{f\in F}\sum_{m\in M_i} X^U_{c,v,i,f,m} \quad i \in I \tag{5}$$

$$\sum_{f\in F} X^D_{c,p,f} \le 1 \quad p \in P,\ c \in C_p \tag{6}$$

$$X^D_{c,p,f} = \sum_{i\in I}\sum_{m\in M_i} X^L_{c,v,f,i,m} \quad p \in P,\ c \in C_p,\ f \in F,\ v = 1 \tag{7}$$

$$\sum_{f\in F} X^D_{c,p,f} \le \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X^L_{c,v,f,i,m} \quad p \in P,\ c \in C_p \tag{8}$$

$$\sum_{f\in F} X^D_{c,p,f} = \sum_{v\in V}\sum_{i\in I} X^R_{c,v,i,p} \quad p \in P,\ c \in C_p \tag{9}$$

$$\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X^L_{c,v,f,i,m} \le \sum_{f\in F} X^D_{c,p,f} \quad p \in P,\ c \in C_p,\ v \in V \tag{10}$$

$$\sum_{i\in I}\sum_{f\in F}\sum_{m\in M_i} X^U_{c,v,i,f,m} \le \sum_{f\in F} X^D_{c,p,f} \quad p \in P,\ c \in C_p,\ v \in V \tag{11}$$

$$\sum_{f\in F}\sum_{m\in M_i} X^L_{c,v,f,i,m} = X^R_{c,v,i,p} +$$

$$\sum_{f\in F}\sum_{m\in M_i} X^U_{c,v,i,f,m} \quad p \in P,\ c \in C_p,\ v \in V,\ i \in I \tag{12}$$

$$\sum_{i\in I}\sum_{f\in F}\sum_{i'=i}\sum_{f'\in F}\left(X^L_{c,v,f,i,m} - X^U_{c,v,i',f',m}\right) \ge 0 \quad c \in C,\ v \in V,\ m \in M_i \tag{13}$$

$$\sum_{i\in I}\sum_{m\in M_i} X^U_{c,v-1,i,f,m} \le \sum_{i\in I}\sum_{m\in M_i} X^L_{c,v,f,i,m} \quad c \in C,\ f \in F,\ v > 1 \tag{14}$$

$$X^L_{c,v+1,f,i,m} \le \sum_{f'\in F}\sum_{i'\in I}\sum_{m'\in M_i} X^L_{c,v,f',i',m'} \quad c \in C, f \in F, i \in I, m \in M_i, v < |V| \tag{15}$$

$$\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X^L_{c,v+1,f,i,m} \le \sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X^L_{c,v,f,i,m} \quad c \in C,\ v < |V| \tag{16}$$

$$maxt\ \sum_{f\in F} X^D_{c,p,f} \ge \sum_{f\in F}\left(\frac{dpf_{p,f}}{vd_{p,f}}\right) X^D_{c,p,f} +$$

$$\sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i}\left(\frac{dfi_{f,i}}{vl_{f,i}} + tload_f + tunload_i\right) X^L_{c,v,f,i,m} +$$

$$\sum_{v\in V}\sum_{i\in I}\sum_{f\in F}\sum_{m\in M_i}\left(\frac{dif_{i,f}}{vu_{i,f}}\right) X^U_{c,v,i,f,m} +$$

$$\sum_{v\in V}\sum_{i\in I}\left(\frac{dip_{i,p}}{vr_{i,p}}\right) X^R_{c,v,i,p} \quad p \in P,\ c \in C_p \tag{17}$$

$$X^L_{c,v,f,i,m}, X^U_{c,v,i,f,m}, X^R_{c,v,i,p}, X^D_{c,p,f} \in \{0,1\} \tag{18}$$

The aim of the proposed model is to minimize total transportation costs (Z), including costs per traveled kilometers (with and without load) and fixed costs per used trucks. Eq. (1) defines this objective function. The first four terms correspond to the costs for the different movements that constitute a trip while the last one represents the fixed costs per use of trucks. Parameters $cd_{p,f}$, $cl_{f,i}$, $cu_{i,f}$ and $cr_{i,p}$ represent the costs per

kilometer traveled (in $/km) between the corresponding nodes, *cfix* is the fixed cost per use of truck (in $) and the parameters $dpf_{p,f}$, $dfi_{f,i}$, $dif_{i,f}$ and $dip_{i,p}$ define the distances (in km) between the corresponding nodes.

Constraints (2) and (3) establish the maximum supply for each harvest area and the demand to be satisfied for each plant, respectively. Constraints (4) and (5) establish the node balances, that is, the number of trips that arrive at each harvest area / plant must coincide with the number of trips that departs from those nodes.

Restrictions (6) state that a truck can arrive at most once to a harvest area coming from its regional base, while restrictions (7) state that if a truck departs from the regional base, it must perform a loaded movement to any plant in its first trip.

Restrictions (8) state that if a truck is used, then it must perform at least one loaded movement. Constraints (9) force each truck to return to the regional base from which it started its route, while restrictions (10) and (11) establish that if a truck is not used then it must not have any loaded movement assigned.

In constraints (12) it is established that, after completing a loaded movement, the truck can either return to the regional base to finish the route or go to a harvest area to perform a new loaded movement.

Restrictions (13) guarantee that if a loaded movement is not performed, the associated unloaded movement must not be performed either. In addition, when a route is made up of more than one trip, before making an unloaded movement to return to the regional base (on the last trip) the corresponding loaded movement must be completed (equations (14)).

To avoid alternative solutions, the trips are created in ascending order, that is, if the trip v is not performed, neither does the trip $v + 1$ (constraints (15) and (16)).

Finally, in restrictions (17) the maximum time of use of a truck is defined (the working day is limited by *maxt* hours). Parameters $vd_{p,f}$, $vl_{f,i}$, $vu_{i,f}$ and $vr_{i,p}$ represent the average speed between the nodes (in km/h) while $tload_f$ and $tunload_i$ define the average loading (in harvest area) and unloading (in plant) times (in h), respective. Constraints (18) establish the nature of the involved variables.

4 Solution approach

Due to combinatorial nature of this type of formulation, the (P1) model for large-size problems cannot be optimally solved in a reasonable computing time. Therefore, in this section a solution approach is proposed in order to reduce the solution times. A closer look on the structure of the problem presented in the previous section shows that constraints (2) to (5) are coupling the trucks, while the remaining restrictions are dealing with each truck separately. This structure strongly suggests that the problem could be decomposed into a Master Problem (MP) with the linking constraints and a Sub-Problem (SP) per truck. A CG based approach appears to be an appropriate method to tackle the problem.

The idea behind CG is that many linear programs are too large to consider explicitly all the variables. Since most of the variables are non-basic and take value zero in the optimal solution, only a subset of variables needs to be considered when

solving the problem. CG takes advantage of this idea to generate only variables which have the potential to improve the objective function, that is, to find variables with negative reduced costs (for a minimization problem). In other words, in this methodology the original problem is decomposed into a MP and a SP: the first decides which variable (or column) is used while the second generates such variables (or columns). There is an extensive literature about CG; for further details, the reader is recommended the works by Desaulniers et al. [11] and Lübbecke and Desrosiers [12].

Thus, the original formulation (P1) is decomposed into a MP, in which only the constraints that links the trucks are considered (constraints (2) to (5)), and a SP per truck, including the rest of the restrictions (constraints (6) to (17)). The decision variables in the MP are related to used route (that is, which column is selected, Y_r), while in the SP the variables are related to the conformation of the routes (that is, which column is generated). According to the formulation proposed in this work, each generated column contains the information about the trips involved in the route (combination of movements from regional base to harvest area, between harvest area and plants, and from plants to regional base). The solution approach used in this work is presented in Fig. 2.

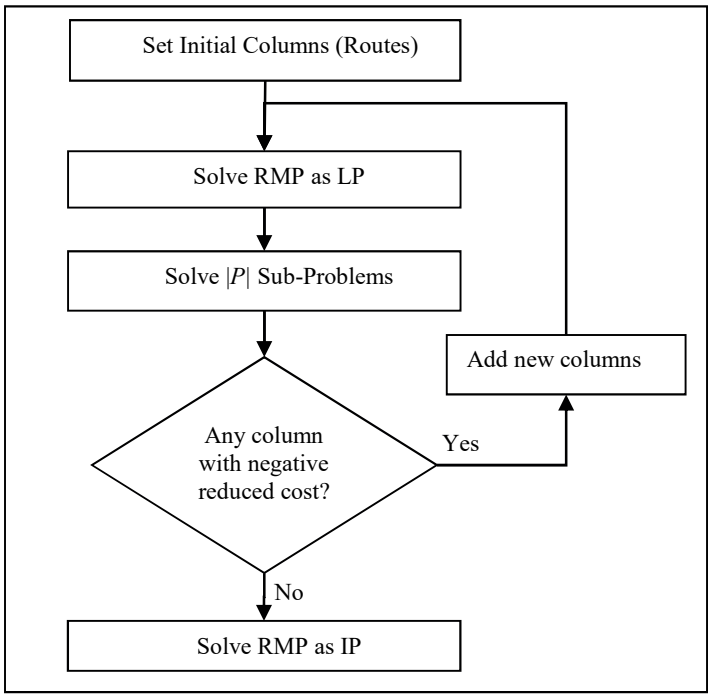

Fig. 2. Column generation-based approach

The algorithm presented in Fig. 2 performs the following: first, the initial columns (initial routes) are generated. After that, the relaxation of the Restricted Master

Problem (RMP), i.e., the MP with a limited number of columns or variables is solved to determine which columns (routes) are used and the corresponding dual information is obtained. With that information (the values of the dual variables are fixed as parameters), the SP is solved for each regional base p to obtain new columns. If one or more columns with negative reduced costs are obtained, they are added to the RMP and the process is repeated. Otherwise, the RMP is solved as IP (with the already generated columns) to obtain a feasible integer solution to the problem.

The MP model is the following:

$$\min Z_{MP} = \sum_{r \in R^+} croute_r \, Y_r \tag{19}$$

Subject to:

$$\sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} \sum_{i \in I} A^{XL}_{p,v,f,i,m,r} \, Y_r \leq supply_{f,m} \quad f \in F, \;\; m \in M_i \tag{20}$$

$$\sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} \sum_{f \in F} A^{XL}_{p,v,f,i,m,r} \, Y_r \geq demand_{i,m} \quad i \in I, \;\; m \in M_i \tag{21}$$

$$\sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} \sum_{i \in I} A^{XL}_{p,v,f,i,m,r} \, Y_r = \sum_{r \in R^+} \sum_{p \in P} A^{XD}_{p,f,r} \, Y_r + \sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} \sum_{i \in I} \sum_{m \in M_i} A^{XU}_{p,v,i,f,m,r} \, Y_r \quad f \in F \tag{22}$$

$$\sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} \sum_{f \in F} \sum_{m \in M_i} A^{XL}_{p,v,f,i,m,r} \, Y_r = \sum_{r \in R^+} \sum_{p \in P} \sum_{v \in V} A^{XR}_{p,v,i,r} \, Y_r + \sum_{r \in R^+} \sum_{p \in P} \sum_{f \in F} \sum_{m \in M_i} \sum_{v \in V} A^{XU}_{p,v,i,f,m,r} \, Y_r \quad i \in I \tag{23}$$

$$\sum_{r \in R^+} \sum_{f \in F} A^{XD}_{p,f,r} \, Y_r \leq ntrucks_p \quad p \in P \tag{24}$$

$$Y_r \in \{0, 1\} \tag{25}$$

Regarding the objective function, it consists of the minimization of the routing cost Z_{MP} (Eq. (19)), where $croute_r$ represents the cost of the feasible route r. Constraints (20) to (23) correspond to equations (2) to (5) of the original formulation, respectively. Restriction (24) must be incorporated into the MP model to consider the size of the truck fleet belonging to the regional base p, that is, the number of routes beginning at regional base p must be less or equal than the number of available trucks in that regional base ($ntrucks_p$). R^+ is the set of all feasible routes and the parameters $A^{XD}_{p,f,r}$, $A^{XL}_{p,v,f,i,m,r}$, $A^{XU}_{p,v,i,f,m,r}$ and $A^{XR}_{p,v,i,r}$ contain the information about the composition of each route r.

As was previously mentioned, since it is not practical to consider all feasible routes, the CG procedure works with a subset of them ($R^- \subseteq R^+$), where R^- is the set of the already generated routes. Thus, the RMP model is given by constraints (19) to (24), relaxing the binary condition of Y_r.

Since the truck fleet is homogeneous, it is not necessary to solve $|C|$ sub-problems (that is, a sub-problem per vehicle). It suffices to solve one SP per regional base considered, i.e. $|P|$ sub-problems, because the possible routes to be performed by each truck belonging to the regional base p are the same. Thus, the SP model is the following:

$$\min Z_{SP}^{p} = \sum_{f\in F} cd_{p,f}\ dpf_{p,f}\ X_f^{DSP} + \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} cl_{f,i}\ dfi_{f,i}\ X_{v,f,i,m}^{LSP}$$
$$+ \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} cu_{i,f}\ dif_{i,f}\ X_{v,i,f,m}^{USP} + \sum_{v\in V}\sum_{i\in I} cr_{i,p}\ dip_{i,p}\ X_{v,i}^{RSP}$$
$$+ \sum_{f\in F} cfix\ X_f^{DSP} - \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} \pi_{f,m}^{1}\ X_{v,f,i,m}^{LSP}$$
$$- \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} \pi_{i,m}^{2}\ X_{v,f,i,m}^{LSP}$$
$$- \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} \pi_{f}^{3}\left(X_f^{DSP} + X_{v,i,f,m}^{USP} - X_{v,f,i,m}^{LSP}\right)$$
$$- \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} \pi_{i}^{4}\left(X_{v,f,i,m}^{LSP} - X_{v,i,f,m}^{USP} - X_{v,i}^{RSP}\right) - \pi^{0} \quad (26)$$

Subject to:

$$\sum_{f\in F} X_f^{DSP} \le 1 \quad (27)$$

$$X_f^{DSP} = \sum_{i\in I}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} \quad f\in F,\ v=1 \quad (28)$$

$$\sum_{f\in F} X_f^{DSP} \le \sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} \quad (29)$$

$$\sum_{f\in F} X_f^{DSP} = \sum_{v\in V}\sum_{i\in I} X_{v,i}^{RSP} \quad (30)$$

$$\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} \le \sum_{f\in F} X_f^{DSP} \quad v\in V \quad (31)$$

$$\sum_{i\in I}\sum_{f\in F}\sum_{m\in M_i} X_{v,i,f,m}^{USP} \le \sum_{f\in F} X_f^{DSP} \quad v\in V \quad (32)$$

$$\sum_{f\in F}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} = X_{v,i}^{RSP} + \sum_{f\in F}\sum_{m\in M_i} X_{v,i,f,m}^{USP} \quad v\in V,\ i\in I \quad (33)$$

$$\sum_{i\in I}\sum_{f\in F}\sum_{i'=i}\sum_{f'\in F}\left(X_{v,f,i,m}^{LSP} - X_{v,i',f',m}^{USP}\right) \ge 0 \quad v\in V,\ m\in M_i \quad (34)$$

$$\sum_{i\in I}\sum_{m\in M_i} X_{v-1,i,f,m}^{USP} \le \sum_{i\in I}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} \quad f\in F,\ v>1 \quad (35)$$

$$X_{v+1,f,i,m}^{LSP} \le \sum_{f'\in F}\sum_{i'\in I}\sum_{m'\in M_i} X_{v,f',i',m'}^{LSP} \quad f\in F, i\in I, m\in M_i, v<|V| \quad (36)$$

$$\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X_{v+1,f,i,m}^{LSP} \le \sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i} X_{v,f,i,m}^{LSP} \quad v<|V| \quad (37)$$

$$maxt\ \sum_{f\in F} X_f^{DSP} \ge \sum_{f\in F}\left(\frac{dpf_{p,f}}{vd_{p,f}}\right) X_f^{DSP} +$$
$$\sum_{v\in V}\sum_{f\in F}\sum_{i\in I}\sum_{m\in M_i}\left(\frac{dfi_{f,i}}{vl_{f,i}} + tload_f + tunload_i\right) X_{v,f,i,m}^{LSP} +$$
$$\sum_{v\in V}\sum_{i\in I}\sum_{f\in F}\sum_{m\in M_i}\left(\frac{dif_{i,f}}{vu_{i,f}}\right) X_{v,i,f,m}^{USP} + \sum_{v\in V}\sum_{i\in I}\left(\frac{dip_{i,p}}{vr_{i,p}}\right) X_{v,i}^{R} \quad (38)$$

$$X_{v,f,i,m}^{LSP}, X_{v,i,f,m}^{USP}, X_{v,i}^{RSP}, X_f^{DSP} \in \{0,1\} \quad (39)$$

Constraint (26) performs the pricing (it determines the reduced costs), i.e., this objective function evaluates if the generated route could potentially improve the

objective function of the RMP model by incorporating it into the R^- set. The dual variables correspond to Eqs. (20) to (24) and are given by $\pi^1_{f,m}$, $\pi^2_{i,m}$, π^3_f, π^4_i and π^0, respectively. The aim of the $|P|$ sub-problems is to determine the route with the most negative reduce cost. Constraints (27) to (38) are related to restrictions (6) to (17) of the (P1) model; in turn, since the SP model is solve by regional base p (regardless of the truck c for which the route is created) the variables $X^D_{c,p,f}$, $X^L_{c,v,f,i,m}$, $X^U_{c,v,i,f,m}$ and $X^R_{c,v,i,p}$ must be rewritten as follows:

$$X^{DSP}_f = \sum_{r\in R^+}\sum_{p\in P} A^{XD}_{p,f,r}\, Y_r \quad f \in F \tag{40}$$

$$X^{LSP}_{v,f,i,m} = \sum_{r\in R^+}\sum_{p\in P} A^{XL}_{p,v,f,i,m,r}\, Y_r \quad f \in F, v \in V, i \in I, m \in M_i \tag{41}$$

$$X^{USP}_{v,i,f,m} = \sum_{r\in R^+}\sum_{p\in P} A^{XU}_{p,v,i,f,m,r}\, Y_r \quad f \in F, v \in V, i \in I, m \in M_i \tag{42}$$

$$X^{RSP}_{v,i} = \sum_{r\in R^+}\sum_{p\in P} A^{XR}_{p,v,i,r}\, Y_r \quad v \in V, i \in I \tag{43}$$

A set of initial routes is required to proceed with the column generation algorithm. All unitary length routes that can be made (regardless of the actual number of available trucks) are generated so as to achieve the first dual solution and thus initialize the CG algorithm. There are several heuristic techniques for route generation. In this work, a linear programming model (a classical transportation problem) is used to obtain the minimum supply distances traveled with load. Subsequently, this solution is converted into routes of unitary length (that is, routes with a single trip).

5 Illustrative example

To test both the mathematical programing model (P1) and the CG based algorithm, an example is developed. The considered supply chain involves 5 plants that demand 5 types of raw materials, which can be obtained from 15 harvest areas. There are 750 available trucks (spread across 12 regional bases) for hauling a total of 750 full-truckloads demanded by the plants. In Table 1 the used parameters are presented. In addition each truck can make at most 3 loaded trips beyond considering its maximum available working time (*maxt*). In

Table **2** supply and demand of raw materials are detailed. The distances between the nodes are presented in Table 3.

Table 1. Model parameters.

Parameter	Value	Parameter	Value	Parameter	Value
$cd_{p,f}$	0.8 $/km	$vd_{p,f}$	65 km/hr	$tload_f$	0.5 hr
$cl_{f,i}$	1.2 $/km	$vl_{f,i}$	55 km/hr	$tunload_i$	0.5 hr
$cu_{i,f}$	0.8 $/km	$vu_{i,f}$	65 km/hr	*cfix*	30 $
$cr_{i,p}$	0.8 $/km	$vr_{i,p}$	65 km/hr	*maxt*	10 hr

Table 2. Supply / demand of raw materials (in full-truckloads).

	m_1	m_2	m_3	m_4	m_5
f_1	14	21	11	7	15
f_2	11	7	3	10	10
f_3	1	15	12	12	11
f_4	11	1	10	13	3
f_5	16	9	18	12	21
f_6	17	11	11	9	11
f_7	13	11	17	5	1
f_8	16	6	3	13	21
f_9	6	8	15	1	15
f_{10}	15	21	5	13	6
f_{11}	8	4	10	21	10
f_{12}	11	21	11	11	10
f_{13}	3	11	21	14	6
f_{14}	11	15	11	16	15
f_{15}	17	9	13	13	15
i_1	35	50	-	-	40
i_2	50	85	40	-	-
i_3	35	-	50	15	-
i_4	30	15	30	60	50
i_5	-	-	30	75	60

Table 3. Distances between the nodes (in kilometers).

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}	p_{11}	p_{12}	i_1	i_2	i_3	i_4	i_5
f_1	32	70	70	120	100	100	82	58	136	164	158	45	71	50	120	114	108
f_2	61	114	20	150	61	85	22	78	82	108	98	81	106	40	32	92	60
f_3	30	85	14	125	54	70	22	50	86	114	106	50	78	14	60	81	58
f_4	50	100	14	136	50	73	10	64	76	103	94	67	92	32	40	81	51
f_5	91	130	54	156	57	85	40	95	61	81	71	102	121	73	10	86	50
f_6	45	81	30	114	32	51	14	45	64	92	85	51	72	36	54	60	36
f_7	36	40	76	90	85	78	81	36	121	148	143	22	41	58	122	92	95
f_8	45	54	54	86	32	32	42	20	67	94	89	32	45	50	81	45	41
f_9	85	90	73	103	14	32	51	63	22	50	45	76	80	81	67	28	10
f_{10}	73	51	82	64	36	10	67	36	60	82	81	50	41	80	99	22	45
f_{11}	113	112	98	114	42	51	76	89	10	22	20	103	102	108	81	40	36

$\mathbf{f_{12}}$	108	95	102	92	41	36	81	78	28	40	41	92	85	108	95	22	40
$\mathbf{f_{13}}$	91	36	112	28	72	45	100	51	92	110	110	60	32	104	135	51	81
$\mathbf{f_{14}}$	110	64	124	40	72	45	108	71	81	92	95	82	58	120	136	42	78
$\mathbf{f_{15}}$	60	30	81	58	51	32	71	20	81	104	102	32	20	73	108	45	61
$\mathbf{i_1}$	63	10	92	51	71	51	86	28	100	124	122	32	71	50	120	114	108
$\mathbf{i_2}$	22	86	20	130	67	81	36	54	100	128	120	50	106	40	32	92	60
$\mathbf{i_3}$	90	134	51	163	64	92	41	98	71	91	81	104	78	14	60	81	58
$\mathbf{i_4}$	89	73	90	76	32	14	71	57	41	61	60	71	92	32	40	81	51
$\mathbf{i_5}$	78	91	63	108	10	36	41	61	28	57	50	73	121	73	10	86	50

All the models are implemented and solved in GAMS [13] 24.7.3 version, using CPLEX 12.6.3 solver in an Intel(R) Core(TM) i7-4790, 3.60 GHz.

The (P1) model involves 978,750 binary variables and 448,601 equations. This formulation cannot be solved in one hour of execution using the selected solver. However, if the resolution time limit in (P1) is removed, the optimal solution (0% optimality gap) is found in 70,285 s (near 20 hours). The optimal solution has an objective value equal to $60,940 and 250 trucks are used to satisfy the demand. Each truck completes 3 loaded movements in their respective route.

By applying the CG based approach, the solution is reached in 122.95 s (resolution time of the column generation phase: 121.42 s; resolution time of the final RMP: 1.53 s). The final RMP involves 9,820 binary variables (columns) and the objective function is equal to $60,964, while 250 trucks are used (also making 3 trips each). As it can be noted, the proposed solution approach reaches a solution with a difference of 0.039% in the objective function given by the (P1) model, but in a considerable shorter resolution time.

It is interesting to note that the solution obtained from the last solved RMP can be used as initial starting point to solve the original formulation (P1) to global optimality. According to this, using a time limit of 15 minutes, then the objective function obtained is equal to $60,948 (0.009% optimality gap). While, if the time limit is omitted, the global optimal solution starting at the RMP solution is reached in 17,234 s, which represents a reduction of 75% with respect to the resolution of the (P1) model without starting point.

Table 4 shows the resolution times for five instances (the case study presented here correspond to the scenario 5). The characteristics of scenarios 1 to 4 are as follows:

- regional bases: 12, 8, 5 and 12, respectively
- plants: 5, 4, 4 and 5, respectively
- types of raw materials: 2, 4, 8 and 8, respectively
- harvest areas: 15, 10, 10 and 15, respectively
- total demand: 150, 250, 150 and 500, respectively.

In this table, “Gen.Time (s)” corresponds to the time needed to generate all the columns (feasible routes); “F.RMP (s)” is the resolution time of the final RMP; “F.RMP gap (%)”, “P1+IP (s)” and “P1+IP gap (%)” represent the optimality gap of the CG-based approach, the (P1) model with initial point and the (P1) model without

initial point, respectively; "Trucks CG", "Trucks P1[a]" and "Trucks P1[b]" represents the number of used trucks in the CG-based approach, in the (P1) model with initial point and in the (P1) model without initial point, respectively; and finally, "P1+IP (s)" and "P1-IP (s)" contain the time needed to solve the (P1) with and without initial point, respectively. It is worth mentioning that the time required to generate the starting point is not included in "P1+IP (s)". From the showed results, it can be derived that both formulations (the (P1) model and the CG-based approach) are effective to solve small/medium-size problems. Clearly, for large size problems, the CG-based approach is an efficient methodology to take into account.

Table 4. Resolution times for all the scenarios.

Scenario	Gen.Time (s)	F.RMP (s)	F.RMP gap(%)	Trucks CG	P1+IP (s)	P1+IP gap(%)	Trucks P1[a]	P1-IP (s)	P1-IP gap(%)	Trucks P1[b]
1	26.16	0.43	0	50	17.24	0	50	18.01	0	50
2	39.29	900	0.032	84	900	0.099	84	900	0.1	84
3	30.98	1.47	0	52	16.91	0	50	21.17	0	50
4	126.81	900	0.046	168	900	0.147	168	-	-	-
5	121.42	1.53	0	250	900	0.009	250	-	-	-

In Table 5 the objective functions of both CG-based approach and (P1) model with the initial point given by CG are compared to the LP relaxation of (P1) for the five scenarios. There is no time limit in the resolution of the LP relaxation of (P1). A time limit of 15 minutes is used in the final RMP and the same time is set for the (P1) model with the starting point defined by the CG-based approach. It is well known that the objective function of LP relaxation represents a lower bound for the objective function of the (P1) model, and therefore the quality of the solution can be assessed.

Table 5. Comparison between the objectives functions.

Scenario	LP Relaxation of P1 ($)	CG-Based Approach ($)	Optimality gap (%)	P1 with Initial Point ($)	Optimality gap (%)
1	10,501.73	10,542.8	0.39	10,517.2	0.147
2	24,362	24,394	0.131	24,384.4	0.092
3	12,733.73	12,912.8	1.387	12,734.8	0.008
4	39,813.33	39,895.2	0.205	39,872	0.147
5	60,935.46	60,964	0.047	60,942	0.011

The obtained results are closer to the LP relaxation of (P1), as can be seen in Table 5, which implies that the proposed approach can be applied in real size problems and guarantee a very good solution in less than 15 minutes of computing time.

6 Final remarks

Transportation planning in forest industry is a critical issue taking into account the high incidence of transportation costs in the profitability of the firms, given the large transported volumes and traveled distances. In the Argentine context, firms generally make decisions regarding the distribution of logs based on their experience. Therefore, the use of a planning tool to make these decisions could lead to significant improvements in the obtained results and the performance of the truck fleet.

In this work, a mathematical programming model is presented. Unlike the previous published works in the literature, the (P1) model simultaneously address product allocation and routing decisions, taking into account different raw materials and several depots or regional bases. In addition, the (P1) model allows determining the size of the truck fleet in such a way to guarantee the supply at minimum cost. The (P1) model is a generalization of the model developed in [8], in which the plants demand a single type of raw material. This generalization allows a better representation of the real problem. The developed mathematical model is robust enough and allows solving problems adjusted to the reality of the Argentine forest industry. In any case, beyond the analyzed example and the obtained results, the formulation could be improved to achieve a more detailed problem description, such as different types of trucks.

From the computational performance point of view, the (P1) model represents a highly combinatorial problem. Therefore, resorting to a CG based approach to solve the model in a reasonable computing time is a crucial aspect, especially if it is intended to have a planning tool that supports logistic planners on a day-to-day basis. An example was analyzed and solved with both solution methods. The CG based approach is able to find a good solution in a short computing time. Since the solution times of the CG based approach depends on the time taken by the column generation phase (the solution times of the sub-problems), it could be improved taking into account acceleration techniques in that phase to achieved a reduction in the total computing time; but this problem is out of the scope of this work and it will be considered in future works.

Finally, it should be noted that, although the CG based approach is not exact (reaching the optimal solution is not guaranteed), it allows obtaining solutions with negligible optimality gap, i.e., solutions very close to the optimal one. This tradeoff between solution quality and solution times makes this approach a viable option for its implementation in a real environment.

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Problema de Recogida y Entrega en la Industria Forestal: nuevos modelos y estudio de su performance*

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Resumen. En el presente trabajo se proponen distintos modelos de Programación Lineal Entera (PLE) que resuelven de forma exacta el problema de ruteo diario de camiones en la industria forestal. El objetivo en todos los casos es generar las rutas de los camiones involucrados a un costo mínimo, mientras se garantiza el suministro de materia prima a las plantas implicadas.
Los modelos que se encuentran habitualmente en la literatura asumen que los viajes que se deben realizar se conocen de antemano o se generan en una etapa previa. A diferencia de esos enfoques, en este trabajo se genera la configuración de cada viaje junto con las decisiones de asignación de materia prima y ruteo.
El modelo propuesto se evalúa en varios escenarios, demostrando en todos ellos que el enfoque propuesto resuelve eficientemente el problema abordado y mejora la performance respecto a los modelos ya existentes en la literatura.

Palabras claves: Ruteo · Industria forestal · Programación matemática · Optimización combinatoria

1. Introducción

En la industria forestal, el transporte de troncos (materia prima) para su distribución desde los puntos de suministro (frentes de cosecha) a las diferentes industrias que los requieren (plantas), representa uno de los factores de mayor impacto en los costos generales. Por lo tanto, hacer más eficientes las operaciones de transporte mediante una planificación adecuada, constituye un ahorro considerable para las empresas del sector, significando una tarea de gran interés.

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En este trabajo se aborda un problema de ruteo que corresponde a una variación del Problema de Recogida y Entrega (PRE): el PRE en el transporte de troncos. El mismo fue definido por Borges y col. en [1] como un conjunto de rutas de vehículos que deben generarse para satisfacer un conjunto de puntos de demanda de acuerdo con un objetivo dado y sujeto a un conjunto de restricciones. Una ruta generalmente comienza y termina en la base de operaciones del vehículo y debe satisfacer diferentes limitaciones de tiempo, como la disponibilidad de horas de trabajo del vehículo (por ejemplo, no permitir trabajar de noche), la duración del turno de trabajo del conductor, las ventanas de tiempo en los puntos de oferta / demanda, etc. Además, los sitios de oferta y demanda se pueden visitar más de una vez (la disponibilidad de materia prima en los puntos de suministro generalmente supera el espacio de carga en los vehículos, así como las demandas de las industrias). Para llevar a cabo el transporte, hay disponible una flota de camiones, que puede consistir en el mismo tipo de camión o en diferentes camiones, cada uno con un conjunto único de características relevantes para el transporte (por ejemplo, capacidad, tipos de materia prima que se permite transportar, consumo de combustible, conjunto de sitios no permitidos o imposibles de visitar, etc.). Los camiones se distribuyen en un conjunto de sitios o se ubican en una sola base. Por lo tanto, el problema del transporte de troncos involucra muchas decisiones complejas, que incluyen una gran cantidad de camiones, nodos de oferta y demanda, diferentes tipos de materia prima, varios puntos de partida y aspectos legales y políticos, entre otros, lo que hace que el proceso de resolución sea muy complejo. Así, el desarrollo de una herramienta capaz de representar y resolver este problema de manera eficiente y en un corto tiempo de cómputo, supone un desafío relevante para la industria forestal.

Debido a la complejidad de este tipo de problemas y la dificultad para obtener una solución óptima en un tiempo de cómputo razonable, en la literatura se propusieron muchos enfoques basados en heurísticas (algunos de ellos pueden encontrarse en [2–4], entre otros). Son menos los enfoques exactos publicados, recientemente, Bordón y col. [5], presentaron una formulación exacta a través de un modelo de Programación Mixta Entera Lineal que simultáneamente genera rutas ordenando secuencias de viajes y asigna camiones a las rutas.

En el presente trabajo se proponen distintos modelos de Programación Lineal Entera (PLE) para la resolución de PRE en el transporte de troncos en forma exacta. Estos modelos mejoran la performance respecto a los existentes.

En la siguiente sección, se describe el problema a modelar. En la Sección 3 se presentan la función objetivo y las restricciones involucradas en los modelos matemáticos propuestos. En la sección 4 se trabaja en la evaluación de la performance de los mismos a través de la consideración de diferentes instancias. Finalmente, en la última sección, se exponen las conclusiones.

2. Descripción del problema

La Cadena de Suministro (CS) considerada cuenta con un conjunto M de materias primas, distribuidas en un conjunto de frentes de cosecha $F = \cup_{m \in M} F_m$,

donde F_m denota el conjunto de los frentes de cosecha que ofrecen la materia prima m. Cada frente $f \in F_m$ posee una cantidad disponible $Oferta_{f,m}$ de materia prima m (expresada en número de cargas completas de camiones). Estos abastecen a un conjunto de plantas $P = \cup_{m \in M} P_m$, donde P_m denota el conjunto de plantas que demandan la materia prima m. Cada planta $p \in P_m$ exige cierta cantidad de materia prima $Demanda_{p,m}$ (también expresadas en cargas completas de camiones).

Se dispone de una flota de camiones homogénea $c \in C$ distribuidos en un conjunto de bases regionales B. Se denota con C_b el conjunto de camiones en la base $b \in B$. Así, $C = \cup_{b \in B} C_b$. Cada camión $c \in C_b$ para $b \in B$, comienza y termina su ruta en la base regional b.

Por cuestiones gremiales, el tiempo destinado a cada ruta no podrá superar un determinado tiempo máximo $Max\,T$. Cada ruta es una sucesión de viajes. Consideraremos 4 tipos de viajes.

I) El primer viaje (descargado) de cada camión c que se realiza desde la base regional de c hacia un frente de cosecha.
II) Los viajes (cargados) desde frentes de consecha donde cada camión recoge materia prima y se dirige hacia una planta que la demande.
III) Los viajes (descargados) en los que, desde una planta el camión se dirige a un frente de cosecha.
IV) El último viaje (descargado) de cada camión en el cual este regresa a su base regional desde una planta.

Ciertas regulaciones imponen un número máximo lim de viajes que componen una ruta, sin importar si el camión tiene tiempo para realizar más viajes sin superar el tiempo $Max\,T$. Por lo tanto, cada ruta es una sucesión de viajes v, $v \in V = \{v_i : 1 \leq i \leq lim\}$. Cada camión transporta a lo sumo un tipo de materia prima $m \in M$ en cada viaje y, si va cargado, lo hace con la carga completa.

El costo total de transporte $TCOST$ que se busca minimizar es la suma de los costos de las rutas que realizan los camiones. Estos constan de dos partes: un costo fijo por camión utilizado y un costo variable que depende de los kilómetros recorridos por cada camión, si el camión se encuentra descargado o no, y las características de la carretera (tipo de pavimento, geografía, etc.). Así, para cada $b \in B$ y $f \in F$, $WUa_{b,f}$ denota el costo de realizar el viaje (descargado) desde la base regional b hasta el frente de cosecha f. Este costo está compuesto por la suma del costo fijo (en \$) de utilizar un camión de la base b más el costo de recorrer la distancia entre la base y el frente, proporcional a la distancia entre ellos. Adicionalmente, para cada $c \in C$, $f \in F$ y $p \in P$, $WL_{f,p}$, $WUb_{p,f}$ y $WUc_{p,b}$ son, repectivamente, el costo de realizar el viaje desde el frente de cosecha f hasta la planta p (cargado), desde la planta p hasta el frente de cosecha f (descargado) y desde la planta p hasta la base regional b (descargado). Estos costos son porporcionales a la distancia entre cada par de sitios.

También, para cada $b \in B$, $f \in F$ y $p \in P$, $TUa_{b,f}$, $TL_{f,p}$, $TUb_{p,f}$ y $TUc_{p,b}$ denotan, repectivamente, la duración (en horas) del viaje desde la base b al frente de cosecha f, desde el frente de cosecha f hasta la planta p (cargado), desde la

planta p hasta el frente de cosecha f (descargado) y desde la planta p hasta la base regional b (descargado).

3. Modelo de PLE

En esta sección se describe la función objetivo y se presentan las restricciones a considerar, las cuales se clasifican en las restricciones necesarias para la conformación de las rutas posibles, las restricciones que evitan soluciones alternativas y desigualdades adicionales válidas. Las primeras restricciones resuelven en el problema de ruteo de troncos, mientras que las dos últimas se consideran para evaluar si su inclusión en modelo mejora la performance del solver.

Las rutas de los camiones se describen como una sucesión de viajes que realizan. Así, para cada camión c, tenemos una variable binaria que determina cuál es el i-ésimo viaje $v_i \in V$ que realiza c. Formalmente, para cada $c \in C$, $f \in F$, $p \in P$, $m \in M$ y $v \in V$ tenemos las siguientes variables:

- $x^{v_1}_{c,f,m}$: toma el valor 1 si el camión c comienza su ruta y se dirige al frente f para cargar materia prima m.
- $x^{v_i}_{c,f,p}$, con i par : toma el valor 1 si el camión c en su i-ésimo viaje se dirige desde el frente f a la planta p.
- $x^{v_i}_{c,p,f,m}$, con $3 \leq i \leq lim - 2, i$ impar : toma el valor 1 si el camión c en su i-ésimo viaje se dirige desde la planta p al frente f para cargar materia prima m.
- $x^{v_i}_{p,c}$, con $i \geq 3, i$ impar : toma el valor 1 si el camión c en su i-ésimo viaje regresa a su base desde la planta p.

3.1. Función objetivo

El costo total de transporte TCOST que se busca minimizar, se modela como sigue:

$$\begin{aligned}\text{TCOST} = &\sum_{b\in B}\sum_{c\in b}\sum_{m\in M}\sum_{f\in F_m} WUa_{b,f}\, x^{v_1}_{c,f,m} + \\ &\sum_{c\in C}\sum_{v\in V_{par}}\sum_{m\in M}\sum_{f\in F_m}\sum_{p\in P_m} WL_{f,p}\, x^{v}_{c,f,p} + \\ &\sum_{c\in C}\sum_{v\in V_{impar}}\sum_{p\in P}\sum_{m\in M}\sum_{f\in F_m} WUb_{p,f}\, x^{v}_{c,p,f,m} + \\ &\sum_{b\in B}\sum_{c\in b}\sum_{v\in V_{impar}}\sum_{p\in P} WUc_{p,b}\, x^{v}_{p,c}, \end{aligned} \tag{1}$$

donde V_{impar} y V_{par} denotan los subconjuntos de V dados por

$$V_{impar} = \{v_i \in V : i \text{ es impar }, i \geq 3\} \quad \text{y} \quad V_{par} = \{v_i \in V : i \text{ es par }\}.$$

3.2. Restricciones que modelan las rutas posibles

- *A lo sumo una ruta por camión*
  Cada camión puede salir a lo sumo una vez desde su base regional y, en caso de hacerlo, debe dirigirse hacia un frente de cosecha:

$$\sum_{m \in M} \sum_{f \in F_m} x^{v_1}_{c,f,m} \leq 1, \ \ \forall c \in C. \tag{2}$$

- *Restricciones de conservación de flujo*
  Si un camión se utiliza, debe regresar a su base regional (y sólo puede hacerlo desde una planta):

$$\sum_{m \in M} \sum_{f \in F_m} x^{v_1}_{c,f,m} = \sum_{v \in V_{impar}} \sum_{p \in P} x^{v}_{p,c}, \ \ \forall c \in C. \tag{3}$$

  Si un camión desde su base regional se dirige a un frente de cosecha a recoger una determinada materia prima, en su segundo viaje debe dirigirse hacia una planta que requiera esta materia prima:

$$\sum_{p \in P_m} x^{v_2}_{c,f,p} = x^{v_1}_{c,f,m}, \, \forall c \in C, \, \forall m \in M, \, \forall f \in F_m. \tag{4}$$

  Del mismo modo, en los viajes subsecuentes desde un frente de cosecha que ofrece la materia prima m, el camión debe dirigirse hacia una planta que demande la materia prima m:

$$\sum_{p \in P} x^{v}_{c,p,f,m} = \sum_{p \in P_m} x^{v+1}_{c,f,p}, \ \ \forall c \in C, \ \ \forall v \in V_{impar}, \, \forall m \in M, \, \forall f \in F_m, \tag{5}$$

  (notar que, por definición, si $v \in V_{impar}$, entonces $v \geq 3$).
  Por otro lado, cada camión desde una planta puede regresar a su base regional o dirigirse hacia un frente de cosecha:

$$\sum_{f \in F} x^{v}_{c,f,p} = \left[x^{v+1}_{p,c} + \sum_{m \in M} \sum_{f \in F_m} x^{v+1}_{c,p,f,m} \right], \ \ \forall c \in C, \, \forall v \in V_{par}, \, \forall p \in P. \tag{6}$$

- *Tiempo máximo de duración de una ruta*
  La siguiente ecuación calcula el tiempo total en la carretera $TIME_c$ de cada camión $c \in C$. El mismo se obtiene sumando los tiempos utilizados en cada viaje.

$$\begin{aligned} TIME_c = & \sum_{m \in M} \sum_{f \in F_m} TUa_{b,f} \ x^{v_1}_{c,f,m} + \\ & \sum_{v \in V_{par}} \sum_{f \in F} \sum_{p \in P} TL_{f,p} \ x^{v}_{c,f,p} + \\ & \sum_{v \in V_{impar}} \sum_{f \in F} \sum_{p \in P} TUb_{p,f} \ x^{v}_{c,p,f} + \\ & \sum_{v \in V_{impar}} \sum_{p \in P} TUc_{p,b} \ x^{v}_{p,c}. \end{aligned} \tag{7}$$

La restricción (18) establece que cada camión no puede permanecer en la carretera más tiempo que $MaxT$:

$$TIME_c \leq MaxT, \quad \forall c \in C. \tag{8}$$

- *Límite de oferta y satisfacción de la demanda*
  La cantidad de materia prima disponible en cada frente de cosecha y la cantidad demandada de la misma por cada planta se expresan en términos del número de cargas completas de camiones. Por lo tanto, la cantidad total de viajes cargados con cada tipo de materia prima m que se realizan desde el frente de cosecha f a cualquier planta no pueden exceder la disponibilidad de ese tipo de materia prima en ese frente, denotada por $Oferta_{f,m}$:

$$\sum_{c \in C}(x^{v_1}_{c,f,m} + \sum_{p \in P} \sum_{v \in V_{impar}} x^{v}_{c,p,f,m}) \leq Oferta_{f,m}, \ \ \forall m \in M, \forall f \in F_m, \tag{9}$$

  Por otro lado, la cantidad total de viajes cargados de cierto tipo de materia prima m que llegan a la planta p deben cumplir con la demanda de esta planta $Demanda_{p,m}$:

$$\sum_{c \in C} \sum_{f \in F_m} \sum_{v \in V_{par}} x^{v}_{c,f,p} = Demanda_{p,m}, \ \ \forall m \in M, \forall p \in P_m. \tag{10}$$

Hasta aquí, si un camión c tiene asignada una ruta (la restricción (2) se satisface por igualdad para c), las restricciones de conservación de flujo ((3), (4), (5) y (6)) aseguran que esa ruta corresponda a un circuito que se inicia y termina en la base asociada al camión y, los viajes entre frentes de cosecha y plantas, se efectúan consecutivamente en forma correcta. Además las restricciones (8) aseguran que dicho tour no supere el tiempo máximo permitido para el camión en la carrretera. Las restricciones (9) y (10) imponen las condiciones de oferta y de demanda.

Llamaremos *Modelo A* al modelo que cuya función objetivo minimiza la expresión $TCOST$ (ecuación (1)), sujeto a las restricciones de esta sección: (2), (3), (4), (5), (6), (8), (9) y (10).

3.3. Restricciones que evitan soluciones alternativas

Si en cada base regional la flota de camiones es homegénea, dada una solución factible del *Modelo A*, intercambiando los valores de las variables asignados a dos camiones de una misma base obtenemos una solución factible alternativa, esto es, con mismo costo.

Si suponemos que los camiones en las bases, los frentes de cosecha y las distintas plantas están enumerados, es posible incorporar restricciones que evitan soluciones de este tipo y pueden mejorar la performance computacional del proceso de resolución del modelo. Una primera estrategia es la de ordenar los camiones de una misma base en forma decreciente en función de la duración de sus viajes. Esto es,

$$TIME_c \geq TIME_{c+1}, \quad \forall b \in B, \forall c \in C_b. \tag{11}$$

Estas restricciones también establecen que los camiones de una base salen en orden creciente ya que, si el camión c no viaja ($TIME_c = 0$), entonces tampoco viaja el camión $c+1$ ($TIME_{c+1} = 0$). Esta última condición puede ser modelada como

$$\sum_{m\in M}\sum_{f\in F_m} x^{v_1}_{c+1,f,m} \leq \sum_{m\in M}\sum_{f\in F_m} x^{v_1}_{c,f,m}, \quad \forall b \in B,\, \forall c, (c+1) \in C_b. \tag{12}$$

Otra forma de evitar soluciones alternativas entre camiones de una misma base es eligir las soluciones *monótonas en función de los índices de los camiones, los frentes y las plantas.* A continuación se describen distintas restricciones que cumplen esta tarea.

- "Monotonía camión-frente": las siguientes restricciones imponen que si dos camiones de una misma base se dirigen a dos frentes distintos (a buscar la misma materia prima), entonces el camión de índice menor debe ir al frente de índice menor.

$$x^{v_1}_{c_i,f_r,m} + x^{v_1}_{c_j,f_q,m} \leq 1, \forall b \in B,\, \forall c_i, c_j \in C_b,\, i < j,$$
$$\forall m \in M,\, \forall f_q, f_r \in F_m,\, q < r. \tag{13}$$

  En la Figura 1 se representa el tipo de recorrido que se está evitando. Es fácil ver que dada una solución representada por x que viole la desigualdad (13), o sea, tal que $x^{v_1}_{c_i,f_r,m} = x^{v_1}_{c_j,f_q,m} = 1$ para ciertos $c_i, c_j \in C_b$ con $i < j$ y $f_q, f_r \in F_m$ con $q < r$, podemos encontrar una solución z con el mismo costo que x que satisfaga la desigualdad (13). En efecto, si $x^{v_1}_{c_i,f_r,m} = x^{v_1}_{c_j,f_q,m} = 1$, entonces $x^{v_1}_{c_i,f_q,m} = x^{v_1}_{c_j,f_r,m} = 0$. Definimos z tal que $z^{v_1}_{c_i,f_r,m} = z^{v_1}_{c_j,f_q,m} = 0$, $z^{v_1}_{c_i,f_q,m} = z^{v_1}_{c_j,f_r,m} = 1$ y el resto de los viajes de z que coincidan con los de x. Claramente z verifica las restricciones de (2) a (10). Además, z satisface (13) y tiene el mismo costo que x.

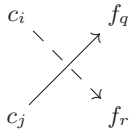

Figura 1. Viajes que evita la restricción (13) donde $c_i, c_j \in C_b$ para cierta base regional b, $i < j$, $f_q, f_r \in F_m$ para cierta materia prima m y $q < r$.

- "Monotonía frente-planta": las siguientes restricciones imponen que si dos camiones de una misma base, desde un mismo frente de cosecha se dirigen a dos plantas distintas (a llevar la misma materia prima), entonces el camión de índice menor debe ir a la planta de índice menor.

$$x^{v}_{c_i,f,p_r} + x^{v'}_{c_j,f,p_q} \leq 1, \forall v, v' \in V_{par},\, \forall b \in B,\, \forall c_i, c_j \in C_b,\, i < j,$$
$$\forall m \in M,\, \forall f \in F_m,\, \forall p_q, p_r \in P_m,\, q < r. \tag{14}$$

En la Figura 2 se representa el tipo de recorrido que se está evitando. Con un razonamiento análogo al anterior, es fácil ver que dada una solución x que viole la desigualdad (14), podemos encontrar una ruta z con el mismo costo que x que satisfaga la desigualdad (14).

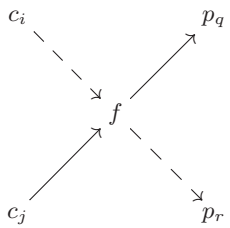

Figura 2. Viajes que evita la restricción (14) donde $c_i, c_j \in C_b$ para cierta base regional b, $i < j$, $p_q, p_r \in P_m$ para cierta materia prima m que ofrece el frente f y $q < r$.

- "Monotonía planta-frente": las siguientes restricciones imponen que si dos camiones de una misma base desde una misma planta se dirigen a dos frentes de cosecha distintos, entonces el camión de índice menor debe ir al frente de índice menor.

$$x^{v}_{c_i,p,f_r,m} + x^{v'}_{c_j,p,f_q,m} \leq 1, \forall v, v' \in V_{impar}, \forall b \in B, \forall c_i, c_j \in C_b, i < j \\ \forall p \in P, \forall m \in M, \forall f_q, f_r \in F_m, q < r. \quad (15)$$

En la Figura 3 se representa el tipo de recorrido que se está evitando. Como antes, se puede probar que dada una solución x que viole la desigualdad (15), podemos encontrar una solución z con el mismo costo que x que satisfaga la desigualdad (15).

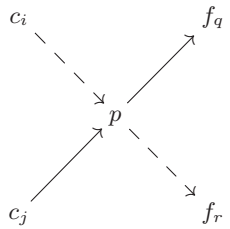

Figura 3. Viajes que evita la restricción (15) donde $c_i, c_j \in C_b$ para cierta base regional b, $i < j$, $p \in P$, $f_q, f_r \in F_m$ para cierta materia prima m y $q < r$.

- "Monotonía planta-base": las siguientes restricciones imponen que si dos camiones de una misma base llegan a una misma planta y uno se dirige a un

frente de cosecha mientras el otro regresa a su base, entonces el camión de menor índice sea el que retorna a su base.

$$x^v_{c_i,p,f,m} + x^v_{p,c_j} \leq 1, \forall v \in V_{impar}, \forall b \in B, \forall c_i, c_j \in C_b, i < j \\ \forall m \in M, \forall f \in F_m, \forall p \in P. \quad (16)$$

En la Figura 4 se representa el tipo de recorrido que se está evitando. Notar que, dada una solución x que viole la desigualdad (16), siguiendo la demostración realizada en el caso de la restricción (13) con menores cambios, podemos encontrar una solución z con el mismo costo que x que satisfaga la desigualdad (16).

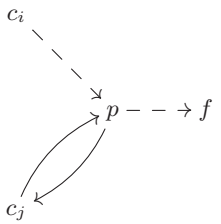

Figura 4. Viajes que evita la restricción (16) donde $c_i, c_j \in C_b$ para cierta base regional b, $i < j$, $p \in P$ y $f \in F$.

Con estas restricciones pueden aún sobrevivir soluciones simétricas correspondientes a dos camiones de una misma base cuyas rutas demoran el mismo tiempo pero sólo si esas rutas están compuestas por los mismos viajes y en el mismo orden.

3.4. Desigualdades válidas adicionales

A continuación se presentan desigualdades válidas que, aunque no ajustan la región factible de la relajación lineal del *Modelo A*, en experiencias computacionales sobre distintos escenarios se observa que alteran la performance del solver.

- Si el camión c no se utiliza entonces, no realiza viajes entre frentes y plantas.

$$\sum_{p \in P} \sum_{m \in M} \sum_{f \in F_m} x^v_{c,p,f,m} \leq \sum_{m \in M} \sum_{f \in F_m} x^{v_1}_{c,f,m}, \quad \forall c \in C, \forall v \in V_{impar}. \quad (17)$$

- Un camión que regresa a su base no realiza ningún otro viaje posteriormente. Esta condición se representa con las restricciones (18) y (19):

$$\sum_{f \in F} \sum_{p \in P} x^t_{c,f,p} \leq 1 - x^v_{p',c}, \quad \forall c \in C, \forall p' \in P, \forall v \in V_{impar}, \forall t \in V^{[v+1]}_{par}, \quad (18)$$

$$\sum_{p\in P}\sum_{m\in M}\sum_{f\in F_m} x^t_{c,p,f,m} \leq 1 - x^v_{p',c}, \quad \forall c \in C,\ \forall p' \in P,$$
$$\forall v \in V_{impar},\ \forall t \in V^{[v+2]}_{impar}, \qquad (19)$$

donde $V^{[v+1]}_{par}$ y $V^{[v+2]}_{impar}$ denotan, respectivamente, los conjuntos

$$\{t \in V_{par} : t \geq v+1\} \quad \text{y} \quad \{t \in V_{impar} : t \geq v+2\}.$$

Las restricciones (18) y (19) pueden combinarse de la siguiente manera:

$$\sum_{t\in V^{[v+1]}_{par}} \left[\sum_{f\in F}\sum_{p\in P} x^t_{c,f,p} + \sum_{p\in P}\sum_{m\in M}\sum_{f\in F_m} x^{t+1}_{c,p,f,m}\right] \leq (lim-3)(1 - x^v_{p',c}),$$
$$\forall c \in C,\ \forall p' \in P,\ \forall v \in V_{impar}, \quad (20)$$

o como sigue

$$\sum_{f\in F}\sum_{p\in P} x^t_{c,f,p} + \sum_{p\in P}\sum_{m\in M}\sum_{f\in F_m} x^{t+1}_{c,p,f,m} \leq \frac{lim-3}{2}(1 - x^v_{p',c}),$$
$$\forall c \in C;\ \forall p' \in P,\ \forall v \in V_{impar},\ \forall t \in V^{[v+1]}_{par}. \quad (21)$$

4. Análisis de la performance del enfoque

En esta sección, se evalúan las capacidades y el rendimiento de distintos modelos que se intengran por las restricciones presentadas en la sección anterior. Se presentan diversos escenarios basados en el contexto argentino, extraídos del trabajo de Bordón y col. [5]. En la Tabla 1 se establece la cantidad de camiones disponibles, bases regionales, frentes de cosecha, tipos de materia prima, plantas y demandas para cada instancia.

En todos los casos, se consideran los siguientes parámetros: el costo de utilización por camión es de $30, cada camión puede hacer un máximo de 7 viajes y cada ruta no puede exceder las 10 horas, la velocidad promedio del camión con y sin carga es igual a 55 y 65 km/h, respectivamente para todas las carreteras, los costos por kilómetro recorrido con y sin carga equivalen a 1.2 y 0.8 $/km, respectivamente, para todas las carreteras. Así las constantes $WUa_{b,f}$, $WL_{f,p}$, $WUb_{p,f}$ y $WUc_{p,b}$ se calculan como el producto de la distancia por el costo correspondiente por kilómetro recorrido con o sin carga, respectivamente; y las constantes $TUa_{b,f}$, $TL_{f,p}$, $TUb_{p,f}$ y $TUc_{p,b}$ como el cociente entre la distancia entre los lugares que intervienen y la velocidad promedio del camión con o sin carga, respectivamente.

Para la evalución de la performance todos los modelos se implementan y resuelven en la versión 24.7.3 de GAMS (ver [6]), utilizando el solver CPLEX 12.6.3 en un Intel(R) Core(TM) i5-2500k, 3.30 GHz.

Tabla 1. Características de cada escenario estudiado.

Escenario	Camiones diponibles	Bases regionales	Plantas	Tipos de materia prima	Frentes de cosecha	Demanda
1	50	1	1	1	5	100
2	120	1	1	1	5	300
3	400	1	1	1	5	1000
4	50	1	3	1	5	100
5	120	1	3	1	5	300
6	120	1	5	1	5	300
7	300	1	5	1	5	750
8	70	5	1	1	10	150
9	200	5	1	1	10	500
10	70	5	3	2	10	150
11	200	5	3	2	10	500
12	70	5	5	3	10	150
13	200	5	5	3	10	500
14	100	12	1	1	15	200
15	400	12	1	1	15	750
16	500	12	2	2	35	1000
17	100	12	3	3	15	200
18	100	12	5	5	15	200
19	400	12	5	5	15	750
20	400	12	6	3	15	750

4.1. Modelo A

En primera instancia se analiza el *Modelo A* que, como ya se dijo, considera las restricciones que definen las rutas posibles: restricciones de la (2) a la (10) (ver subsección 3.2). En la Tabla 2 se muestran los resultados obtenidos. El límite de tiempo fijado para la resolución es de 300 segundos de CPU. Solo dos escenarios (3 y 16) no llegan a la solución óptima antes del límite de tiempo. Estos casos involucran el mayor número de camiones disponibles (400 y 500) y demandas requeridas (1000 cargas de camiones completas). Aunque el óptimo global en estos ejemplos no se alcanza en el tiempo límite fijado, el modelo encuentra una solución con un gap de optimalidad razonable (menos del 1 %).

A continuación se describe la solución completa de uno de los escenarios considerados con el fin de mostrar las potencialidades de esta formulación como una herramienta práctica para la industria.

Considerar la CS del caso 5, compuesta por 3 aserraderos, 5 frentes de cosecha y 1 base regional. Se dispone de 120 camiones para transportar 300 cargas completas de camiones de una materia prima única. Las distancias entre los frentes de cosecha y las plantas, entre la base regional y las plantas, entre la base regional y las áreas de cosecha, la disponibilidad de materia prima y las demandas de las plantas se muestran en la Tabla 3.

El modelo comprende 1248 variables binarias y 3849 ecuaciones. Se resuelve en 2.36 seg. con 0 % de gap de optimalidad y el valor de la función objetivo

Tabla 2. Estadísticas del *Modelo A* para cada escenario.

Escenario	Variables discretas	Ecuaciones	Tiempo CPU (seg.)	GAP	Costo total	Camiones utilizados
1	1900	1307	3.23	0.00 %	18484.0	34
2	4561	3127	6.59	0.00 %	61712.0	110
3	15201	10407	300.00	0.49 %	202486.0	337
4	5200	1609	0.89	0.00 %	11390.0	34
5	1248	3849	2.36	0.00 %	29165.2	100
6	20400	4571	3.66	0.00 %	44350.4	100
7	51000	11411	6.66	0.00 %	116351.2	250
8	5110	3232	0.44	0.00 %	28893.6	50
9	14600	9212	0.70	0.00 %	58698.8	167
10	20930	6464	2.02	0.00 %	16217.2	50
11	59800	18424	12.23	0.00 %	57968.4	167
12	45150	8853	5.33	0.00 %	22444.8	50
13	129000	22029	16.61	0.00 %	75013.6	167
14	10800	6617	0.59	0.00 %	31276.4	67
15	43200	26417	1.88	0.00 %	114455.2	250
16	353000	144573	300.00	0.04 %	105025.6	334
17	59400	19249	14.23	0.00 %	23449.6	67
18	144000	31881	11.55	0.00 %	22944.4	67
19	576000	127281	262.91	0.00 %	84062.0	250
20	457200	80452	89.83	0.00 %	69596.0	250

Tabla 3. Distancias (en km) entre los nodos involucrados en el escenario 5 y cantidad de materia prima disponible y demandada (en cargas de camiones completos).

	p_1	p_2	p_3	b_1	Materia prima disponible (en cargas de camiones completos)
f_1	50	41	72	72	83
f_2	50	100	58	32	42
f_3	45	40	22	30	65
f_4	28	72	81	67	70
f_5	86	114	61	50	51
b_1	41	70	28		
Demanda (en cargas completas de camiones)	150	70	80		

es igual a $29165.2. En este caso se utilizan 100 camiones que realizan rutas compuestas por 7 viajes, es decir, el mayor número de viajes permitidos para cada camión. En la Tabla 4, por razones de espacio, solo se presentan algunas rutas de camiones para que se puedan apreciar las características de la solución. A partir de esta se puede detallar la sucesión de viajes que realiza cada camión y el tiempo total requerido para cada una de estas, las cargas que se usaron de cada frente de cosecha y las que quedaron luego de satisfacer todas las demandas (ver Tabla 5). Por ejemplo, el camión c_2 abastece en todos sus viajes a la planta p_1, la primera carga proviene del frente de cosecha f_2 mientras que las dos restantes desde f_4. En total requiere de 3.91 horas para esta tarea desde que sale hasta que regresa a la base regional. Como se puede ver en la Tabla 4, la duración de las rutas de los camiones es relativamente corta y todas se componen de 7 viajes, que es el límite fijo. La duración media de las rutas es de 4,43 horas. Por lo tanto, si se permiten más viajes por camión, se pueden utilizar una menor cantidad de camiones.

Tabla 4. Descripción de las rutas de los camiones de la solución óptima para el escenario 5.

Camión	Viaje 1	Viaje 2	Viaje 3	Viaje 4	Viaje 5	Viaje 6	Viaje 7	Duración de la ruta (h)
c_2	$b_1 - f_2$	$f_2 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - b_1$	3,91
c_3	$b_1 - f_1$	$f_1 - p_2$	$p_2 - f_1$	$f_1 - p_2$	$p_2 - f_1$	$f_1 - p_1$	$p_1 - b_1$	5,40
...	...	...	...	...	...	...	...	...
c_{50}	$b_1 - f_3$	$f_3 - p_2$	$p_2 - f_1$	$f_1 - p_2$	$p_2 - f_1$	$f_1 - p_1$	$p_1 - b_1$	4,74
c_{51}	$b_1 - f_5$	$f_5 - p_3$	$p_3 - f_3$	$f_3 - p_3$	$p_3 - f_3$	$f_3 - p_3$	$p_3 - b_1$	3,79
...	...	...	...	...	...	...	...	...
c_{119}	$b_1 - f_2$	$f_2 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - b_1$	3,91
c_{120}	$b_1 - f_2$	$f_2 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - f_4$	$f_4 - p_1$	$p_1 - b_1$	3,91

En la Tabla 5 se puede observar que las plantas, en el óptimo, son abastecidas por un subconjunto de frentes de cosecha, y en casos como p_1 y f_4, se advierte que hay frentes de cosecha dedicados exclusivamente al suministro de una sola planta. Además, en los casos de f_1, f_2, f_3 y f_4, se distribuye la cantidad total de cargas completas de camiones disponibles y, por lo tanto, sería beneficioso extender la cantidad de materia prima disponible allí.

4.2. Modelos alternativos

Buscando mejorar la performance del *Modelo A*, sobretodo en los escenarios donde no se alcanza la solución óptima, se realizaron experiencias computacionales con 27 modelos distintos de PLE obtenidos agregando las restricciones descriptas en las secciones 3.3 y 3.4 en diversas combinaciones. En la mayoría de los casos no se dieron cambios notables en los tiempos de resolución.

El modelo a destacar es el que llamaremos *Modelo B* compuesto por las restricciones del *Modelo A* más las desigualdades válidas (18) y (19). Los resultados

Tabla 5. Cantidad de viajes cargados generados entre frentes de cosecha y plantas en el escenario 5 y cantidad de materia prima sobrante.

	p_1	p_2	p_3	Materia prima sobrante (en cargas completas de camiones)
f_1	38	45		
f_2	42			
f_3		25	40	
f_4	70			
f_5			40	11

obtenidos para este modelo se detallan en la Tabla 6. Notar que, a diferencia del *Modelo A*, en este caso se alcanza la solución óptima para el escenario 16.

Cabe mencionar que en estos problemas en donde existen soluciones alternativas, no solo influye el tamaño del problema en la eficiencia computacional, sino también los valores de los parámetros y los tradeoffs entre ellos. Por tal motivo, en casos como el escenario 3, en donde el número de variables discretas es menor que en otros escenarios, el modelo no llega al óptimo global en el tiempo de cómputo límite.

Tabla 6. Estadísticas del *Modelo B* para cada escenario.

Escenario	Variables discretas	Ecuaciones	Tiempo CPU (seg.)	GAP	Costo total	Camiones utilizados
1	1900	1607	3.84	0.00 %	18484.0	34
2	4561	3847	6.42	0.00 %	61712.0	110
3	15201	12807	300.00	0.63 %	202486.0	337
4	5200	2509	0.53	0.00 %	11390.0	34
5	1248	6009	2.48	0.00 %	29165.2	100
6	20400	8171	4.56	0.00 %	44350.4	100
7	51000	20411	8.95	0.00 %	116351.2	250
8	5110	3652	0.30	0.00 %	28893.6	50
9	14600	10412	0.69	0.00 %	58698.8	167
10	20930	7724	2.08	0.00 %	16217.2	50
11	59800	22024	44.34	0.00 %	57968.4	167
12	45150	10953	5.30	0.00 %	22444.8	50
13	129000	28029	29.31	0.00 %	75013.6	167
14	10800	7217	0.39	0.00 %	31276.4	67
15	43200	28817	2.28	0.00 %	114455.2	250
16	353000	150573	121.31	0.00 %	105009.6	334
17	59400	21049	15.75	0.00 %	23449.6	67
18	144000	34881	12.94	0.00 %	22944.4	67
19	576000	139281	300.00	0.00 %	84062.0	250
20	457200	94852	53.88	0.00 %	69596.0	250

5. Conclusiones

La planificación del transporte en la industria forestal es un problema crítico teniendo en cuenta la alta incidencia de los costos de transporte en la rentabilidad de las empresas, dados los grandes volúmenes de materia prima que se deben transportar y las distancias que se deben recorrer. Esta industria presenta características específicas que generan muchas rutas alternativas. Esto genera un problema altamente combinatorio. Un suministro confiable de troncos que permita la disponibilidad de la madera adecuada en el momento apropiado, en el lugar indicado, es una ventaja competitiva.

En el contexto argentino, las empresas generalmente toman decisiones sobre la distribución de troncos en base a su experiencia, es decir, soluciones heurísticas. Por tanto, el uso de una herramienta de planificación para tomar estas decisiones mejora sustancialmente los resultados obtenidos.

Teniendo en cuenta este contexto, en este trabajo se presentaron modelos de PLE para el ruteo de vehículos en la industria forestal. Las formulaciones propuestas permiten generar simultáneamente todas las rutas posibles, evitando la necesidad de proporcionarlas de antemano mediante un largo procesamiento y recurriendo a grandes ordenamientos de datos. Los modelos presentados resuelven la formulación general en un tiempo de cálculo razonable para diversos escenarios de dimensiones reales. Las soluciones obtenidas muestran que los modelos de PLE abordan de manera eficiente y efectiva los objetivos de distribución de troncos, con un alto impacto en la rentabilidad de la industria forestal.

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DESARROLLO DE UN SISTEMA DE PROGRAMACION DE ORDENES DE TRABAJO CON RESTRICCIONES DE SINCRONIZACION PARA UNA EMPRESA DE LA AGROINDUSTRIA DE FLORES

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Resumen. Este trabajo estudia las decisiones logísticas asociadas a la asignación de un conjunto de pedidos de flores a un conjunto de plantas de producción con criterios de eficiencia y equidad. Adicionalmente se consideran restricciones de sincronización para la asignación de los productos con destino a los Estados Unidos. Se implementó un algoritmo de tipo heurístico para optimizar el balance entre oferta y demanda que evalúa tres reglas de ordenamiento de los subpedidos en conjunto con posibles días de desfase. La herramienta permitió resolver instancias con alrededor de 13000 subpedidos. El modelo se válida en un caso real de manufactura del sector agroindustrial de las flores. Los resultados de los experimentos logran demostrar la capacidad del algoritmo para la asignación y sincronización de los subpedidos. Utilizando días de desfase se alcanzaron porcentajes de asignación del 100% de los subpedidos con la regla de ordenamiento aleatoria y minimizando la cantidad de residuo.

Palabras clave: Agroindustria. Cadena de suministro. Problema de asignación. Heurística.

1 Introducción

Desde hace más de 40 años Colombia empezó a posicionarse en el mercado mundial de las flores[1]. El país se convirtió en el segundo exportador de flores de corte en el mundo sólo detrás de Holanda, con una participación del 13,25% de los flujos totales de estos productos[2]. Los Estados Unidos constituyen el principal destino de las exportaciones totales, con una participación del 79,96%, seguido por la Federación Rusa (4%), el Reino Unido (3,66%), Japón (2,73%) y España (2,16%) y para el 2002 dos de cada tres flores que se venden en los Estados Unidos provienen de Colombia.

El problema para trabajar en este proyecto trata de la sincronización en la entrega de producto final en agroindustrias de flores[3] y como se realiza la asignación de órdenes de producción(pedidos)[4] a las diferentes plantas de producción (proveedores), este ejercicio debe ser resultado de una integración de balances de producto, color, variedad, calidad, cantidad, longitud, la relevancia de fechas de despacho entre otros atributos[5]

del producto además de materiales e insumos para ejecutar la orden y la capacidad de proceso que tiene cada una de los proveedores que se encuentra asociados a la unidad logística[6].

El alcance de este documento será la implementación del algoritmo heurístico diseñado en un grupo de empresas exportadoras de flores, a través de una mejora en el aplicativo web con el cual se realizan las labores actualmente[7]. El aplicativo es implementado por la empresa de intermediación logística la cual distribuye los pedidos a sus empresas asociadas. El cambiar la forma en que se asignan los pedidos[8], permite profundizar en la metodología y determinar como la oferta se ajusta mejor a la demanda. Este ejercicio responde a la necesidad de realizar entregas a tiempo y ajustar dentro del proceso logístico las posibles desviaciones de entrega de los subpedidos que componen un pedido entre los proveedores[9] en busca de generar como una agremiación de productores de flores la atención en masa de diferentes clientes[10].

2 Metodología

Para esta investigación se propone un algoritmo heurístico de asignación de pedidos a plantas de producción, que desarrolla los siguientes pasos:

2.1 **Determinar días de desfase:** los días de desfase en el aplicativo que permiten definir una ventana móvil de entrega de los pedidos formada por el límite inferior (fecha de envío – días de desfase) y superior (fecha de envío + días de desfase) que tienen cada uno para ser despachados hacia el cliente final.

2.2 **Ordenar proveedores:** los proveedores son ordenados de forma descendente de acuerdo con su volumen total de tallos y el porcentaje de asignación que tienen cada uno de ellos.

2.3 **Ordenar pedidos:** Los pedidos siempre se ordenan de la fecha de envío más reciente a la fecha de envío más lejana. Luego de este ordenamiento inicial los pedidos se vuelven a ordenar dentro de cada fecha de acuerdo con tres posibles reglas: i) en forma aleatoria (RALE) ii) en forma ascendente (RME, de menor a mayor número total de tallos del pedido), iii) en forma descendente (RMA, de mayor a menor número total de tallos del pedido).

2.4 **Asignar pedidos a proveedores:** La asignación de subpedidos se realiza comparando cada uno de los atributos de la demanda con cada uno de los atributos de la oferta. Para que el pedido sea asignado se debe satisfacer que el proveedor cumpla con la disponibilidad de todos los atributos de la demanda.

2.5 **Estadísticas de asignación:** Después de realizado el proceso de asignación se generan unas medidas de desempeño i) los pedidos asignados, ii) los pedidos no asignados y iii) el porcentaje de asignación.

3 Resultados

El caso de estudio se basa en una oferta de 20.921.788 tallos de flores y una demanda total de 25.058.299 tallos de flores para todas las reglas. Automatizar la opción de "días de desfase" permite generar escenarios de planeación en tiempos muy cortos. Por ejemplo, se asignaron 13 mil subpedidos en un tiempo de 60 segundos. Se evaluaron escenarios de cero, uno y cinco días de desfase en las tres reglas de ordenamiento de pedidos (RMA, RALE, RME). Los resultados de los distintos escenarios se muestran en la Tabla1. Se aprecia que la regla RMA tiene la menor cantidad de residuo (tallos no asignados, disponibles para completar un subpedido), seguida por la regla RALE y con el mayor número de residuo quedaría la regla RME. Esto se debe a que la regla RMA les da prioridad a los pedidos más grandes (mayor número de tallos) mientras que la regla RME deja estos pedidos grandes al final con el resultado de un número mayor de tallos no asignados y a la vez un alto nivel de residuos (tallos de la oferta que no fueron asignados).

Este mismo patrón se cumple con las asignaciones con 5 días de desfase. Es decir, la regla RME tiene la mayor asignación de subpedidos y la regla RMA tiene la mayor asignación de tallos. Mientras que la regla RALE queda en segundo lugar, siempre bastante cercana a la regla ganadora. Es decir, en cantidad de subpedidos no asignados queda cerca a la regla RME y en cantidad de tallos asignados queda cerca a la regla RMA.

De acuerdo con los resultados presentados en los párrafos anteriores, la regla que logra un balance entre la satisfacción del cliente y la utilización de la capacidad de los proveedores es la regla RALE. Debido que a la hora de seleccionar los pedidos no tiene preferencia por los pedidos grandes o pequeños, los cuales tienen la misma probabilidad de ser elegidos. En la Tabla 1. Se muestran los subpedidos no asignados con un día de desfase, se cumple que la regla con el mayor número de subpedidos no asignados es RMA y la regla con el menor número de pedidos no asignados es RME. Sin embargo, es la regla RALE la que combina una menor cantidad de pedidos no asignados y un residuo mínimo. Condición deseada en el desarrollo del algoritmo.

Tabla 1. Numero de subpedidos no asignados y residuo en tallos para cada regla en 3 días de desfase diferentes.

DIAS DE DESFASE	REGLA	SUBPEDIDOS NO ASIGNADOS (Número)	RESIDUO (Tallos)
0	RMA	2.325	7.387.632
	RALE	2.325	7.387.632
	RME	2.325	7.387.632
1	RMA	5.566	53
	RALE	728	245
	RME	339	378.600
5	RMA	10.100	50
	RALE	1.979	185
	RME	136	209.172

4 Conclusiones

El método de asignación usado actualmente genera un 16% de productos disponibles no aprovechados para el cumplimiento de subpedidos. Situación poco favorable para los proveedores quienes buscan el mayor uso de sus productos y que estos retornen en ingresos monetarios para sus compañías. Se propone cambiar el método actual de asignación por un método propuesto que involucra una programación, un algoritmo y la capacidad de realizar centenares de cálculos en unos pocos minutos. El método propuesto permite que las medidas de desempeño puedan pronosticarse y ser definidas con antelación, buscando siempre el desempeño más adecuado en función de la relación recurso, proveedor, cliente. El método propuesto se automatizó en una herramienta que permite plantear escenarios que miden el impacto de la asignación (% de asignacion) y determina con anterioridad la cantidad de pedidos que se pueden cumplir (Pedidos asignados) y cuales no se logran cumplir (pedidos no asignados). Este punto a favor le da una capacidad de reacción al planeador en el proceso de decisión.

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Produccion de biogás y modelado del potencial metanogénico de residuos porcinos y co-sustratos

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Resumen Con el objetivo de incrementar rendimientos metanogénicos en procesos de co-digestión anaerobia, se comparó el Potencial Bioquímico de Metano (PBM) de purín de cerdo y tres co-sustratos: macroalgas, plantas acuáticas, y restos de podas. Adicionalmente, para estimar parámetros cinéticos del bioproceso se implementó el Modelo de Remoción Biológica de Nutrientes N°2 (BNRM2). Los resultados de PBM indican que la macroalga *Spirogyra sp.* posee el mayor potencial para la generación de metano, produciendo 157,2 ± 66,1 $mlCH_4/gSV$, alrededor de tres veces más respecto a los otros co-sustratos. BNRM2 logró ajustar satisfactoriamente el comportamiento observado en las curvas de PBM, permitiendo identificar los parámetros más sensibles. Se concluye que la incorporación de macroalgas en bioprocesos de co-digestión anaerobia contribuye a potenciar la producción de metano. El empleo de BNRM2 en dichos bioprocesos puede servir tanto para estimar parámetros de difícil acceso empírico, como para predecir resultados empleando diversos co-sustratos.

Keywords: Sustentabilidad, Metano, Co-digestión anaerobia, Macroalgas, Modelado, BNRM2.

1. Introducción

En la última década, el crecimiento poblacional de la zona del Alto Valle de Río Negro y Neuquén ha ido acompañado de la intensificación de la producción ganadera, modificando el paisaje y la dinámica del entorno periurbano. La cercanía de los recintos productivos a los aglomerados urbanos exige a los productores la gestión de los residuos que la propia actividad genera, acorde a lo que establece la legislación argentina [15]. Un estudio reciente realizado en el corredor Plottier-Senillosa en la provincia de Neuquén, muestra que solo un 54 % de los productores realizan algún tipo de tratamiento con los residuos de sus animales, entre los que predomina el compostaje (58 %), amontona, junta o estaciona (26 %), solo esparce (11 %), quema (11 %) y amontona y riega (5 %). Entre los encuestados, un 36 % mostró interés por la producción de biogás [5].

Si bien la mayoría de los productores cría dos o más especies de animales, en este estudio nos centramos en dar una solución a la gestión y aprovechamiento de residuos porcinos, tal como el purín de cerdo.

La actividad porcina se relaciona estrechamente con la generación de gases de efecto invernadero. Los niveles de producción de dióxido de carbono (CO_2), metano (CH_4) y óxido nitroso (N_2O) dependen principalmente de las condiciones de cría, de la dieta y del tratamiento y gestión de las excretas. Las emisiones de CO_2 provienen de la exhalación de los cerdos y de la liberación de excretas, el CH_4 se genera en la degradación anaeróbica de la materia orgánica en el tracto digestivo y en las excretas, y el N_20 se genera solo a partir de las excretas, por un proceso incompleto de nitrificación/desnitrificación en la transformación de NH_3 a N_2 [12].Es decir, que un correcto tratamiento a las excretas podría reducir las emisiones de los tres gases de efecto invernadero mencionados. En tal sentido, el tratamiento vía Digestión Anaeróbica (DA) del purín de cerdo presenta importantes ventajas medioambientales, tales como la mitigación de emisiones de CH_4, mediante su acumulación y aprovechamiento energético, reducción de olores, y el aprovechamiento del N a través del uso del digerido como fertilizante orgánico [11]. Dado el moderado potencial metanogénico del purín, la incorporación de sustratos en co-digestión representa una alternativa viable si se desea hacer aprovechamiento energético a la vez que se tratan las excretas. Dada la presencia natural de macroalgas en el Río Limay (Neuquén) y sus alrededores, se consideró el empleo de las mismas como co-sustratos para procesos de DA de purines de cerdo. Diversos estudios han puesto en evidencia el incremento de la producción de metano al utilizar algas como co-sustratos. Por ejemplo, se evaluó una mezcla de algas azules (*Microcystis, Cyclotella, Cryptomonas y Scenedesmus*) como co-sustratos, obteniendo un rendimiento máximo de producción de metano equivalente a 212,7mL/gSV a 35°C [10]. También se llevó a cabo un estudio en donde se utilizó una muestra de *Scenedesmus sp.* como co-sustrato en la co-digestión anaerobia con purín de cerdo, registrando un valor máximo de metano producido de 245mL/gSV a 37°C [2].

Entre los estudios que involucran digestión anaeróbica, es ampliamente utilizado el Modelo de Digestión Anaerobia Nº 1 (ADM1) para representar la dinámica de los procesos que se corresponden con las etapas de degradación de la materia orgánica: hidrólisis, acidogénesis, acetogénesis y metanogénesis. Sin embargo, existen otros modelos, como el Modelo de Remoción Biológica de Nutrientes Nº 2 (BNRM2) [3] que, si bien ha sido mas bien utilizado para representar procesos de depuración de aguas residuales [14, 13] y poco explorado en el modelado de procesos de digestión anaeróbica, presenta algunas ventajas comparativas que resultan atractivas de explorar: considera la acidez en términos de pH, e incluye la actividad de bacterias sulfatorreductoras, lo cuál permite realizar un mejor ajuste en la estimación del rendimiento global de metano.

Los objetivos del presente trabajo incluyen mejorar el rendimiento de la producción de metano en procesos de DA de purines de cerdo, y conocer sus parámetros cinéticos para luego poder aplicarlos en una simulación que estime rendimientos metanogénicos y dinámicas de degradación de los componentes orgáni-

cos. Para ello se hará una comparación del Potencial Bioquímico de Metano (PBM) de tres co-sustratos en la DA de purines de cerdo: macroalgas, plantas acuaticas y restos de poda. Posteriormente se empleará el modelo BNRM2 sobre los resultados obtenidos de PBM, optimizando el ajuste entre resultados experimentales y teóricos, y tratando de identificar aquellos parámetros que tienen mayor influencia en la producción metanogénica.

2. Materiales y Métodos

2.1. Co-digestión anaeróbica de purines

Inóculo El inóculo se generó con el digerido de ensayos de digestión anaerobia llevados a cabo en biodigestores de escala de laboratorio. Se prepararon 4 litros de inóculo en un biorreactor de 6 litros de capacidad, a una temperatura de 35°C dentro de una cámara de cultivo. La alimentación consistió en el reemplazo de 400 ml de purín de cerdo (pH = [7.00-8.20]; Sólidos Totales (ST) = 10.5 % p/p; Sólidos Volátiles (SV) = 2.4 % p/p) cada una semana, o cuando la cantidad de biogás generada por el inóculo disminuyera por debajo de los 50 ml/día. Antes de utilizar el inóculo se lo caracterizó parcialmente según [1], llevando a cabo las siguientes determinaciones: pH = 7.13; conductividad (Λ) = 22.0 mS; Alcalinidad Total (AT) = 2607.1 ± 113 mgCaCO3 (n=2); Alcalinidad Parcial (AP) = 1850 ± 213 mg CaCO3 (n=2); ST = 10.2 ± 0.3 % p/p (n=3); SV = 2.0 ± 0.4 % p/p (n=3).

Sustrato y co-sustratos El sustrato empleado correspondió a purín de cerdo proveniente de un criadero de cerdo de pequeña escala, ubicado en la zona de chacras de la ciudad de Plaza Huincul, Neuquén. Se lo caracterizó mediante las siguientes determinaciones [1]: pH = 7.34; AT = 3005.0 ± 94 mgCaCO3 (n=2); AP = 2034.4 ± 56 mgCaCO3 (n=2); ST = 10.5 ± 0.2 %p/p (n=3); SV = 2.1 ± 0.3 %p/p (n=3). Se utilizaron los siguientes co-sustratos: *Spirogyra sp.* (macroalga verde filamentosa); una mezcla de *Azolla sp.* y *Salvinia sp.* (plantas acuáticas); y restos de poda de *Prunus armeniaca* (planta de damasco). Tanto la macroalga como las plantas acuáticas fueron recolectadas de las orillas del río Limay, a la altura de la ciudad de Neuquén, mientras que los restos de poda de la planta de damasco se recolectaron en una chacra de la ciudad de Plaza Huincul. Todos ellos fueron reducidos a trozos homogéneos mediante el empleo de un cutter. Al igual que ocurrió con el sustrato, a los co-sustratos se les determinó la cantidad de ST y SV; de esta manera se pudo conocer la cantidad inicial de SV en la mezcla de reacción, exhibida en Tabla 1. Los resultados de la determinación de ST fueron: macroalgas = 27.6 ± 0.4 %p/p (n=3); plantas acuáticas = 8.4 ± 1.2 %p/p (n=3); planta de damasco = 80.7 ± 7.3 %p/p (n=3).

Potencial Bioquímico de Metano (PBM) La determinación del PBM de las diferentes mezclas se llevó a cabo según los lineamientos de [7]. El dispositivo empleado como biorreactor fue un frasco de vidrio color caramelo de 150

ml de capacidad total, utilizando un volumen líquido final de 100 ml y un espacio de cabeza de 30 %. La tapa se adaptó para colocar una válvula de paso que se conectó a un sistema de recolección de biogás mediante una manguera de silicona. Dicho sistema consistió en un vaso de acrílico transparente graduado de 100 ml de capacidad, invertido en un recipiente con agua. La determinación de biogás se llevó a cabo por lectura directa del mismo. Para determinar el contenido de metano, el biogás fue extraído con una jeringa y se burbujeó en una solución de NaOH 1N. Luego de agitar durante 5 minutos, para favorecer la disolución del dióxido de carbono en dicha solución, se extrajo nuevamente con la jeringa y se registró el volumen. Posteriormente se llevó a cabo una confirmación cualitativa de la presencia de metano, iniciando una combustión controlada del metano registrado. El ensayo se llevó a cabo por triplicado, tanto para las mezclas sustrato/co-sustrato como para los blancos, respetando una relación inóculo/sustrato de 0.08 ± 0.01 (n=9) y un tiempo de incubación de 25 días. A cada biorreactor se le agregaron 90.0 ml de sustrato (purín), 9.0 ml de inóculo, 0.1 ml de solución de micro y macronutrientes [7], y los siguientes valores de cada co-sustrato según el caso de estudio: 5.5105 ± 0.049g de *Spirogyra sp.*; 2.0209 ± 0.0211g de *Pronus armeniaca*; 6.4710 ± 0.0578g *Salvinia sp.* y *Azolla sp.* Se registraron los valores iniciales en la mezcla de reacción, compuesta por inóculo, sustrato y co-sustrato (Tabla 1). El blanco consistió la misma mezcla de reacción, sin co-sustrato, donde la totalidad de los SV fueron aportados por el purín.

Tabla 1. Características fisicoquímicas de las mezclas de reacción y blanco

Cosustrato	pH	Λ (mS)	SV iniciales (%p/p)
Macroalgas	7.84 ± 0.02 (n=3)	11.20 ± 0.04 (n=3)	1.95 ± 0.00 (n=3)
Planta de damasco	7.46 ± 0.04 (n=3)	8.78 ± 0.37 (n=3)	3.05 ± 0.01 (n=3)
Plantas acuáticas	7.62 ± 0.12 (n=3)	9.68 ± 1.46 (n=3)	2.18 ± 0.00 (n=3)
Blanco	7.67 ± 0.04 (n=2)	8.93 ± 0.37 (n=2)	1.84 ± 0.01 (n=2)

2.2. Modelado Mediante BNRM2

El modelo BNRM2 considera los principales procesos físicos, químicos y biológicos que pueden desarrollarse en una planta de tratamiento. En relación a los procesos anaeróbicos, este modelo describe la evolución de i) bacterias acidogénicas (X_{ACID}) responsables de fermentar la materia rápidamente biodegradable, ii) bacterias acetogénicas (X_{ACET}) las cuales transforman los ácidos grasos volátiles como propiónico en acético e hidrógeno, iii) arqueas metanogénicas acetotróficas (X_{MAC}) responsables de transformar el ácido acético en metano, iv) arqueas metanogénicas hidrogenotróficas (X_{H2}) responsables de transformar el hidrógeno en metano y v) sulfato reductoras (X_{SBR}) las cuales consumen ácidos grasos volátiles e hidrógeno empleando como aceptor final de electrones el ión sulfato. Este ión se encuentra naturalmente en las aguas, y puede alcanzar

concentraciones significativas en el digestor dado que el purín de cerdo se diluye con agua en el procedimiento de limpieza de las camas de los criaderos. Si el agua utilizada proviene de las napas subterráneas, los niveles de ión sulfato pueden ser significativos. La presencia de bacterias sulfato reductoras puede explicar la disminución del metano producido respecto al teórico (290 ml CH_4 /gr SV), por esta razón es importante tenerlas en cuenta. El proceso anaeróbico considerado por el modelo BNRM2, el cual se implementó en Scilab, consta de 12 ecuaciones diferenciales con 32 parámetros. Se consideró que los parámetros más sensibles (aquellos cuya modificación producen una gran variación en la respuesta del modelo) están asociados a las velocidades de crecimiento específicas y las velocidades de lisis de las bacterias y arqueas (μ y b, respectivamente), la constante de hidrólisis de la materia lentamente biodegradable (K_H) y la constante de afinidad a la materia orgánica en el proceso de hidrólisis (K_X). Los valores de los parámetros más sensibles se identificaron por minimización de la suma del cuadrado del error entre los datos experimentales y los estimados por el modelo del volumen de metano acumulado por gramo de sólido volátil obtenido a partir de las experiencias de PBM. Los valores de los restantes parámetros se tomaron de bibliografía [3, 9, 4]. Se consideró que el contenido de sólidos volátiles representa la materia orgánica lentamente biodegradable y que la concentración inicial de sulfato es 50 g S-SO_4/m^3.

3. Resultados y Discusión

3.1. Co-digestión anaeróbica de purines

El PBM para *Spirogyra sp.* en la co-digestión anaeróbica con purines de cerdo mostró 157.2 $\pm$ 66.1 ml CH_4/g SV, triplicando la producción respecto a la digestión de purines con *Prounus armeniaca* (46.1 CH_4/g) y duplicandolá respecto a *Salvinia y Azolla* (70.7 CH_4/g SV). Cabe mencionar que la producción de metano del purín como monosustrato (blanco) fue de 33 ml CH_4/g SV, corroborando que el agregado de co-sustrato mejora el PBM en todos los casos. Los resultados obtenidos sugieren que independientemente del contenido de SV, la matriz interna del co-sustrato condiciona el acceso del consorcio microbiano para su reconversión energética en metano (Fig. 1). Las características bioquímicas de la macroalga, especialmente el contenido de hidratos de carbono, la convierten en un sustrato apropiado para su conversión a biogás [7].

3.2. Implementación del modelo BNRM2

En la Figura 1 se aprecia que el modelo permite ajustar en forma adecuada los datos experimentales de PBM obtenidos tanto para el blanco como para las experiencias de co-digestión.

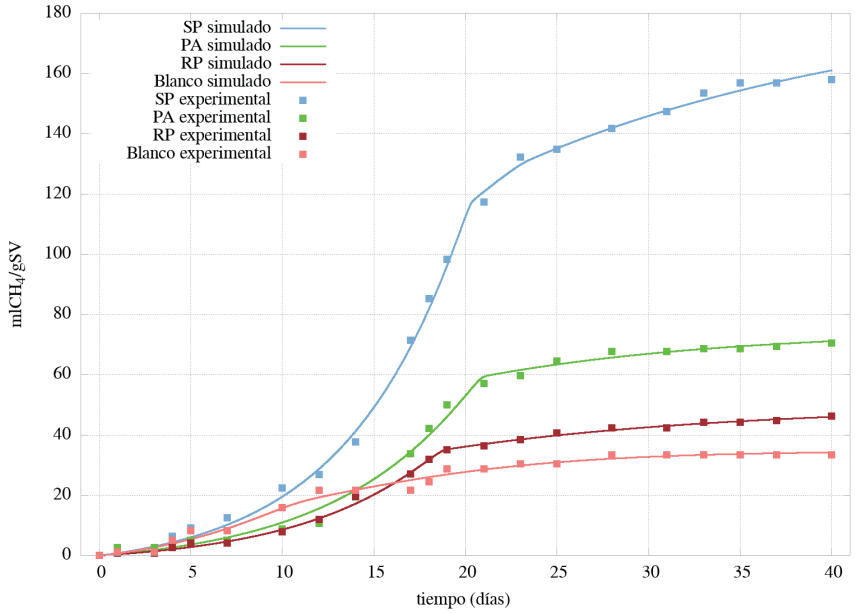

Fig. 1. Datos de PBM experimentales (■) y estimados con el modelo BNRM2 (-) para *Spirogyra sp.* (SP), Plantas Acuáticas (PA), Restos de Poda (RP) y Blanco

Por otro lado, en la Tabla 2 se puede observar que al incorporar un co-sustrato se produce un aumento significativo de la velocidad de hidrólisis de la materia orgánica lentamente biodegradable, lo cual se traduce en un aumento de K_H. Además, se aprecia un aumento en la K_X, o constante de afinidad, indicando que las bacterias acidogénicas son más eficientes para hidrolizar materia orgánica cuando la relación X_S/X_{ACID}, es superior, siendo X_S la materia orgánica lentamente biodegradable. Esto indica una mejora en la eficiencia de hidrólisis a mayores concentraciones de materia orgánica. La velocidad de crecimiento específica de las bacterias acidogénicas disminuye ligeramente en presencia de un co-sustrato, sin embargo, si el co-sustrato es la macroalga *Spirogyra sp.*, aumenta significativamente la velocidad de crecimiento de las acetogénicas. No se observa una variación significativa en los parámetros obtenidos para las arqueas metanogénicas. La materia lentamente biodegradable, puede clasificarse en rápida o lentamente hidrolizable [8, 6]. En base a los resultados obtenidos, el co-sustrato añadido presenta diferentes características de hidrólisis, siendo la macroalga la más fácilmente hidrolizable, de acuerdo a los valores obtenidos de K_H. El ajuste de los valores de los parámetros se llevó a cabo en base a minimizar la suma del cuadrado del error entre los datos experimentales de metano acumulado y los estimados por el modelo. Una mejora sustancial a la optimización se podría

lograr incluyendo en la función de costo los datos de pH, la concentración de ácidos grasos volátiles y de sulfuro de hidrógeno.

Tabla 2. Valores identificados de los parámetros del modelo BNRM2

	Unidad	Blanco	Restos de poda	Plantas Acuáticas	*Spirogyra sp.*
K_h	1/d	4.16	12.92	18.50	21.11
K_x	gDQO/gDQO	149.93	197.67	211.10	268.71
μ_{ACID}	1/d	7.56	2.56	3.53	4.28
b_{ACID}	1/d	0.65	0.14	0.17	0.07
μ_{ACE}	1/d	0.03	0.03	0.05	0.47
b_{ACE}	1/d	0.03	0.03	0.06	0.003
μ_{MAC}	1/d	0.21	0.15	0.14	0.18
b_{MAC}	1/d	0.05	0.003	0.003	0.02
μ_{H2}	1/d	0.05	0.03	0.003	0.04
b_{H2}	1/d	0.10	0.01	0.01	0.06
μ_{SBR}	1/d	0.08	0.32	0.03	1.28
b_{SBR}	1/d	0.002	0.002	0.002	0.001

4. Conclusiones

La producción de metano en procesos de co-digestión anaerobia de purines de cerdo puede incrementarse de manera sustancial con el agregado de diversos co-sustratos. Particularmente *Spirogyra sp.* logró incrementar hasta tres veces la producción de metano respecto a la DA de purín con restos de poda de árbol de damasco, y duplicarla respecto a la mezcla de plantas acuáticas.

Resulta de particular interés haber demostrado que el modelo implementado, BNRM2, describe en forma adecuada la evolución del metano producido en los estudios de PBM. El uso de dicha herramienta permite complementar el desarrollo experimental, posibilitando profundizar en el conocimiento de cada proceso estudiado.

Finalmente, y considerando que tanto los purines de cerdo, como los co-sustratos evaluados, pueden encontrarse en las cercanías de la ciudad de Neuquén, se podría llevar a cabo la gestión de los efluentes porcinos mediante un proceso de co-digestion anaerobia, logrando no solo la producción eficiente de metano, si no que también un tratamiento integral del sustrato y co-sustratos, con posibilidad de un reuso de estos nuevos efluentes. Considerando las ventajas de incorporar *Spirogyra sp.* en los procesos de DA, es factible evaluar la conveniencia de desarrollar cultivos de macroalgas con fines energéticos, en cuyo caso la contribución a la reducción de la huella de carbono y mitigación de los GEI por el tratamiento del purín, se vería incrementada por los procesos de captura de CO_2 de las macroalgas durante su ciclo de vida. De esta manera, se plantea a la co-digestión anaerobia como un proceso sustentable y en armonía con el medio ambiente.

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Evaluación del rendimiento económico y volumétrico de una planificación estratégica en un patrimonio forestal del Norte de la Provincia de Misiones

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Abstract. Forest planning, based on mathematical optimization, makes it possible to model the complexity of a forest system. In this work, two approaches to forest plantation planning were evaluated. Firstly, the aim was to regulate produc-tion and, secondly, to maximise economic benefit. The models proposed give sat-isfactory results and allow different forest management scenarios to be explored efficiently.

Keywords: Strategic planning, Linear programming, Forest Management.

1 Introducción

En el sector forestal, la planificación estratégica de la producción es de gran importancia ya que busca regular la producción y aumentar los ingresos del bosque a fin de garantizar la competitividad [1]. La multidimensionalidad del sistema hace que este proceso sea complejo y el auxilio de modelos matemático algo necesario [2]. La programación lineal es una herramienta robusta para resolver este tipo de problemas. Los primeros modelos aplicados a las ciencias forestales se produjeron en los 60, de la mano de [3], [4] y [5]. Sin embargo, el enfoque de [6] define las bases de la planificación estratégica con el denominado Modelos Tipo I y II. En este trabajo se desarrolló un modelo de planificación forestal, basado en el Modelo Tipo I de [6], con el objeto de evaluar dos escenarios de producción, minimizar la fluctuación de la producción interanual y maximizar el valor actual neto (VAN).

2 Materiales y Métodos

El área de estudio consta de rodales de *Pinus taeda* (Pt), *Pinus elliottii var. elliottii x Pinus caribaea var. hondurensis* (Ph) y *Araucaria angustifolia* (Aa) pertenecientes a un patrimonio forestal ubicado en el norte de la provincia de Misiones. El escenario corresponde a un total de 162 rodales representando una superficie de 3.056 ha, con un rango etario de 1 hasta 36 años de edad.

El patrimonio cuenta con un esquema de manejo forestal típico, que se resume en la Tabla 1. Dentro de las actividades de manejo, se consideraron los siguientes costos: Plantación lograda: 951,51 USD/ha; Poda 1: 114,59 USD/ha; Poda 2: 117,1 USD/ha; Poda 3: 147,82 USD/ha; gastos administrativos: 50 USD/ha/año [7].

Tabla 1. Esquemas de manejo tradicional para las tres especies cultivadas.

Especie	Intervención	Intensidad (%)	Edad (años)
Araucaria angustifolia - Densidad Inicial 2.222 p/ha - 3 podas	1° raleo	50	8
	2° raleo	40	11
	3° raleo	40	15
	4° raleo	40	20
	Tala rasa	100	25
Pinus taeda - Densidad Inicial 1.667 p/ha - 2 podas	1° raleo	55	6
	2° raleo	40	9
	3° raleo	40	13
	Tala rasa	100	18
Pino híbrido - Densidad Inicial 1.333 p/ha - 2 podas	1° raleo	50	7
	2° raleo	40	10
	3° raleo	40	14
	Tala rasa	100	18

El esquema de manejo actual presenta una estructura rígida que no permite un adecuado balance de producción. Además, la empresa define, como nueva política, reemplazar rodales de Aa y Pt por pino hibrido (Ph), ya que este permite obtener aptitudes estructurales iguales o superiores con sus productos y remanufacturas.

Tabla 2. Productos forestales valorados en pie.

Producto (DPF en cm)	Longitud (ft)	Precio (USD/t)
Pt35a99	14	13,88
Pt29a35	14	8,23
Pt25a29	14	3,70
Pt18a25	10	2,37
Pt14a18	10	1,99
PtPul	8	1,21
Ph35a99	14	13,88
Ph29a35	14	8,23
Ph25a29	14	3,70
Ph18a25	10	2,37
Ph14a18	10	1,99
PhPul	8	1,21
Aa35a99	14	36,30
Aa29a35	14	20,68
Aa25a29	14	20,68

Aa18a25	10	9,33
Aa14a18	10	5,66
AaPul	8	1,21

La producción del patrimonio clasificada según sus diámetros en punta fina (DPF) se detalla en la Tabla 2, acompañada de sus valores en pie, calculados a partir de los precios puestos en la industria, menos costos promedio de raleos, cosecha y flete [7].

En la actualidad, la empresa realiza el proceso de planificación de forma empírica, con planilla de cálculo. A partir de la situación se plantea un modelo matemático de optimización y se evalúan dos funciones objetivo (F1 y F2) del mismo modo que [8]. Mediante F1 (1) se busca maximizar el VAN y con F2 (2) se pretende estabilizar la producción global del bosque. Estos modelos se evalúan en 5 escenarios, con un horizonte de planificación (PH) de 50 años, en los que se flexibiliza la edad de tala rasa (ETR), partiendo desde la edad de corta actual (escenario testigo), ± 1 (3 opciones de ETR) y ± 2 años (5 opciones de ETR). En cada uno se reemplaza con la implantación de Ph a los rodales de Aa y Pt al momento de su tala rasa. Además, para el cálculo de la rentabilidad, se utiliza una tasa de actualización del 10 %.

$$MaxVAN = \sum_{i=1}^{M} \sum_{j=1}^{N} VAN_{ij} \times X_{ij} \,; \forall k \tag{1}$$

$$MinDIF = Min(MinMax - MaxMin) \tag{2}$$

Inevitablemente, una función objetivo está ligada a un conjunto de restricciones. La restricción básica (3) se utilizó para indicar la disponibilidad del área máxima de cada rodal y para asegurar que la suma del área de un mismo rodal sea igual a su total, bajo diferentes alternativas de manejo, en ambas FO.

$$\sum_{j=1}^{N} X_{ij} \leq A_i; \forall i \tag{3}$$

Además de esta restricción, la F2 requiere de las restricciones (4) y (5), a fin de minimizar la diferencia entre la producción anual máxima y mínima de madera.

$$\sum_{i=1}^{M} \sum_{j=1}^{N} (VOL_{ijt} X_{ij}) \leq MinMax; \forall t \tag{4}$$

$$\sum_{i=1}^{M} \sum_{j=1}^{N} \left(VOL_{ijt} X_{ij}\right) \geq MaxMin; \forall t \tag{5}$$

Donde *PH* es el horizonte de planificación; VAN_{ij} es el valor actual neto (USD) de la i-ésima posición después de la j-ésima alternativa de gestión; VOL_{ijt} es el volumen (m3) producido en el puesto i-ésimo siguiendo la alternativa de gestión j-ésimo en el período t; *MinMax* es el volumen más bajo de la producción máxima posible en PH; *MaxMin* es el volumen más alto de la producción mínima posible en PH; X_{ij} es la fracción de área (ha) de la posición i-ésima siguiendo la alternativa de gestión j-ésima; A_i es el área total (ha) de la posición i-ésima al comienzo del PH; *M* es el número total de rodales; *N* es el número total de alternativas de gestión de i-ésimo rodal.

El software utilizado para realizar la planificación optimizada es Optimber-LP, desarrollado por la empresa brasileña Optimber Otimização e Informática Ltda. Ésta es una herramienta de planificación forestal estratégica con restricciones tácticas. Esta, a su vez, hace uso del software SIS Pinus, desarrollado por la Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), para la proyección del crecimiento de la masa forestal; y de LINGO, software desarrollado por Lindo Systems Inc., para la resolución del modelo mediante programación lineal. Los datos requeridos para modelar el patrimonio mediante Optimber-LP son: rodal, especie, edad, índice de sitio, superficie, año de plantación, densidad inicial, área basal, altura de poda y número de raleos. Estos fueron obtenidos por la empresa mediante inventarios forestales con fines comerciales. La implementación se llevó a cabo en un computador con Intel Core i5-2310M, CPU@ 2.10 GHz, 8 GB de RAM y SO de 64 bit.

3 Resultados

En la Fig. 1 se pueden ver los resultados de volumen obtenidos para cada uno de los 50 años de PH de cada uno de los productos detallados en la Tabla 2, en base al manejo actual del patrimonio (escenario testigo), es decir, sin flexibilizar la ETR, En este caso se observa una importante oscilación en la producción de rollos, entre 60.000 y 200.000 m^3/año. El principal problema de este manejo radica en la inestabilidad de su producción.

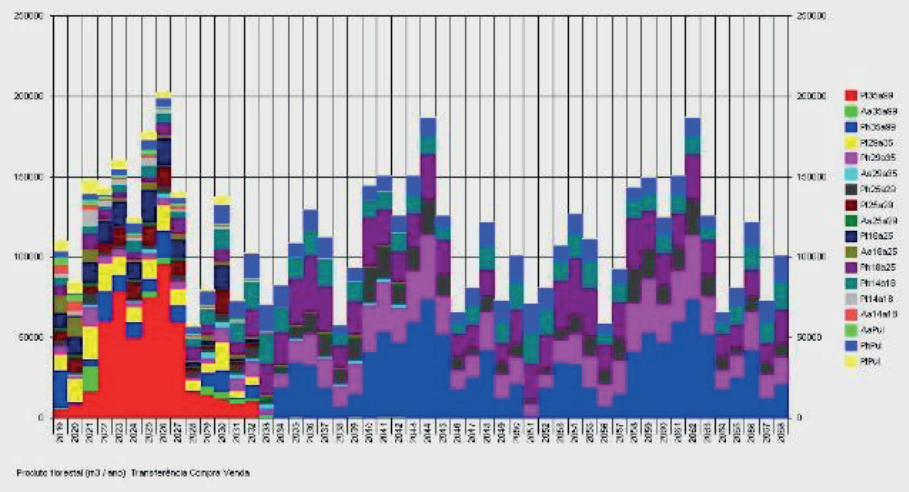

Fig. 1. Volúmenes globales del escenario testigo.

En Fig. 2 se observa que la variación volumétrica se encuentra entre 30.000 y 235.000 m3/año. Por su parte, en la Fig. 3, se observa una mayor variación volumétrica que se encuentra entre los 30.000 y los 300.000 m3/año. Esto se debe a que la F1 busca obtener el mayor rendimiento económico, sin importar la oscilación de su producción.

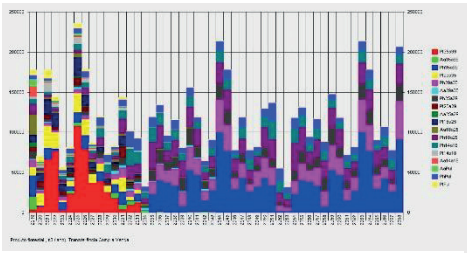

Fig. 2. Comportamiento del volumen aplicando modelo con F1 ± 1.

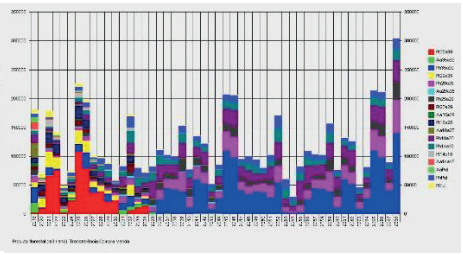

Fig. 3. Comportamiento del volumen aplicando modelo con F1 ± 2.

Por otro lado, la F2 busca estabilizar la producción, esto es, minimizar su variación interanual. Este resultado se aprecia en la Fig. 4, donde la producción de los primeros 10 años es de 135.000 m3/año, y de 105.000 m3/año en los siguientes años, con algunas oscilaciones que llegan a los 135.000 m3/año. También, en la Fig. 5, con una producción volumétrica de 125.000 m^3/año en los primeros 12 años, y 110.000 m3/año en los siguientes 38 años.

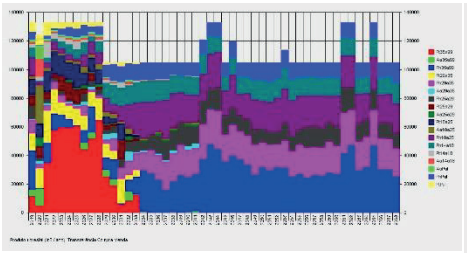

Fig. 4. Comportamiento del volumen aplicando modelo con F2 ± 1.

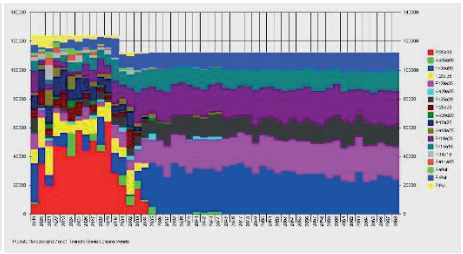

Fig. 5. Comportamiento del volumen aplicando modelo con F2 ± 2.

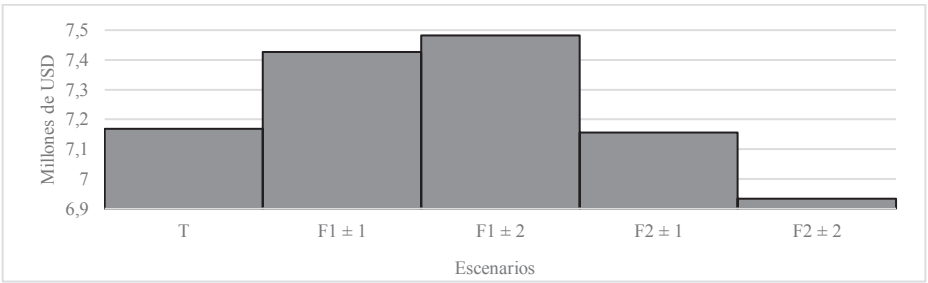

Fig. 6. VAN calculado por escenario.

Los rendimientos económicos de los escenarios simulados se presentan en el Fig. 6. El escenario T rindió 7,17 millones de USD. El escenario F1 ± 1 obtuvo un incremento del 3,5 %. A su vez, el escenario F2 ± 2 fue 4,2 % superior. Por otro lado, los escenarios F2 fueron 0,2 y 3,4 % inferiores a T para ± 1 y ± 2 respectivamente. Resultados lógicos teniendo en cuenta nuevamente el funcionamiento de las FO.

4 Conclusiones

La flexibilización de la ETR conlleva a una mayor estabilidad de la producción, principalmente cuando se utiliza F2; pero además a un mayor rendimiento económico en las simulaciones de F1. La utilización de una u otra dependerá del objetivo global de la organización. Respecto a la rentabilidad, los resultados de F2 fueron expuestos para determinar el costo de estabilizar la producción interanual y, en consecuencia, ordenar el bosque. Posiblemente, esta situación desencadene en una reducción significativa principalmente en los costos fijos operativos si se utilizara un esquema de costos más detallado. Por otro lado, es coherente encontrar mayores rendimientos económicos en la F1, donde el modelo apunta a turnos de corta más largos logrando con esto reducir la superficie afectada a actividades silvícolas, resultando por consecuencia en menores costos y mayores ingresos con productos de diámetros mayores, con mayor relación precio-volumen.

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An integrated approach for solving the bucking and routing problems in the forest industry

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Abstract. In the forest supply chain, decisions related to bucking (cross sectional cuts) and distribution (vehicle routing) activities are usually considered separately and in different planning horizons. This separation between closely related problems gives rise to suboptimal solutions that, if they are simultaneously considered, could bring significant benefits. A tight coordination between the type and amount of material to be harvested and the actually material required to satisfy the daily demand would allow improvements in the efficiency of the production system (both in the forest and in the plant) and significant cost savings. To address this problem, in this work, a mixed integer linear programming (MILP) model that simultaneously considers both decisions is presented. Through a case study, the performance of the developed model is analyzed and the respective conclusions are detailed.

Keywords: Forest Industry, Bucking, Vehicle Routing, MILP.

1 Introduction

Forest supply chain management integrates different operations, such as harvesting, distribution, production, inventory management, among others, which are generally addressed in different planning horizons ([1], [2], [3]). In a context where decisions are made considering one activity, a negative impact can be obtained on another; therefore, it is essential to improve the efficiency of all operations as a whole. A tight coordination between the type and amount of material to be harvested and the actually material required to fulfill the daily demand will allow improvements in the efficiency of the production system and significant cost savings.

In the existing literature, harvesting and transportation problems are often treated with a decoupled approach. In general, harvesting decisions are first addressed in a tactical planning horizon and later, assuming a certain supply from each harvest area to each plant, transportation is organized ([4], [5]). There are situations where, during harvesting, transportation is considered as an additional cost (or a capacity constraint), without detailing how many vehicles will be required for transportation or how distribution will take place ([6], [7], [8]). Although most of these models are

developed for a tactical planning horizon, in daily operations it is generally unknown the effective availability of raw materials in the forests in that period.

The effective availability of raw material is determined through the bucking activity. This activity consists of the transverse cutting of a stem to produce logs of a certain length and diameter, and it can be performed at the destination of the wood (plant or temporary storage sector) or directly in the forest when the stem is harvested. The associated transport activities will then depend on the raw material being transported, stems or smaller logs. The first case is the simplest to address, where it is enough to determine the destination of the harvested stem, while the second case is more complex since transport decisions must necessarily consider aspects related to the load of each truck (logs of the same length must be transported on the same trip, although not necessarily the same diameter). The second approach is addressed in this work.

In this work, a mixed integer linear programming (MILP) model that considers both harvesting and transportation/distribution decisions is proposed. More precisely, it is determined for a weekly planning horizon: the working periods for the harvesting crews, the bucking patterns to be used in each harvest area and the number of logs of a given length and diameter to be obtained, decisions related to log storage in both harvest areas and plants, the truck fleet required to perform the distribution, the routes to be followed by each truck, as well as the composition of the load of each truck (i.e., length of logs to be transported on each trip and the total transported weight). To the best of our knowledge, this is the first time that transportation/distribution decisions and bucking decisions are jointly addressed.

In the following section the problem statement is presented, while in section 3 the proposed MILP model is detailed. In section 4 a case study to analyze the model performance is developed, and finally, in section 5 the final remarks are highlighted.

2 Problem statement

The main assumptions that are taken into account to model the considered problem are described below.

It is considered a set of plants I whose raw material requirements must be covered. It is assumed that at a higher level of planning (that is, annual harvesting planning) the set of harvest areas F to be exploited during the planning period T considered has already been defined.

2.1 Problem characteristics related to harvesting activities

The initial number of standing stems (trees) in each open harvest area f, $f \in F$, $qini_f$, is assumed to be known. In turn, the stems that belong to the same harvest area have identical characteristics (planted forest). It should be noted that the harvesting activities considered in this work are those related to stumpage: thinning activities are not included.

At the end of the planning horizon, there is a desired goal of standing stems in the harvest areas, $qend_f$, which depends on the objectives of the company; in other words, the target level for the harvesting activity at the end of the planning horizon.

The harvesting capacity in a certain period is given by the average productivity of the harvesting crews assigned to that area (previously determined in the annual harvesting planning), that is, the minimum and maximum number of stems that can be harvested in a period ($qcsmin_f$ and $qcsmax_f$, respectively) depends on the number harvesting crews assigned to that harvest area. The cost associated with harvesting crew is not considered because it is included in the annual harvest planning and does not depend on the decisions made in this formulation.

For each harvest area f, there is a set of applicable bucking patterns b, $b \in B$, which was previously determined. Each bucking pattern b is characterized by parameters $nu_{l,d,b}$, that correspond to the number of obtained logs of diameter d and length l when bucking pattern b is applied. Also, the level of losses generated when bucking pattern b is applied, $loss_b$, is considered, and it includes both stem fine tip (i.e. wood not suitable for use) and losses due to the taper of the log (see Fig. 1). These losses have an associated cost per ton of unused wood, $closs_b$.

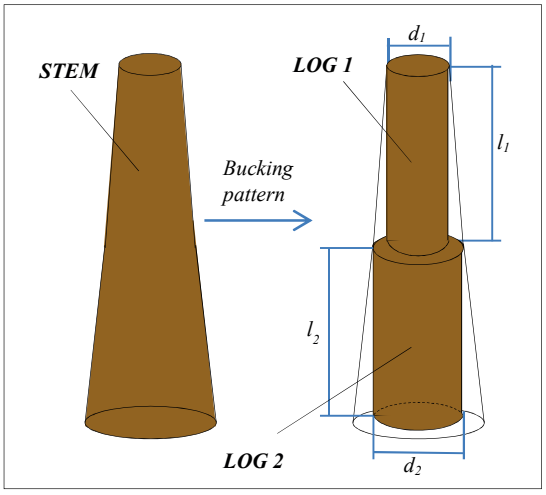

Fig. 1. Useful wood after applying bucking pattern. d: useful diameter, l: length.

Furthermore, it is assumed that if a bucking pattern is applied in a certain harvest area then it must be used at least a minimum number of times, $qminb_b$, in order to avoid setup times and costs. The types of logs that can be obtained by applying the bucking patterns are classified by length l, $l \in L$, and useful diameter d, $d \in D$.

Logs generated in a harvest area can remain on the roadside throughout the planning period without losing quality, in other words, there is no deterioration of the raw material during the planning horizon. However, logs generated in the harvest area f and not distributed at the end of the planning horizon are considered wasted material with an associated cost, $cqrl_{l,d,f}$.

2.2 Problem characteristics related to production activities

Each plant has associated a weekly demand for logs (by length and by diameter), $dtot_{l,d,i}$, which can be covered during any period of the planning horizon, as long as the maximum processing capacity in each plant is respected, $cap_{i,t}$. However, there is a minimum demand for logs of a certain length and diameter that must be satisfied in each period, $dmin_{l,d,i,t}$. This demand is related to the production commitments assumed by the plants. The minimum processing capacity of plants per period is closely related to the minimum demand for logs.

Each plant has a storage yard for logs. Each type of log has an assigned sector in the storage yard, with maximum capacity $maxstock_{l,d,i}$. Each log stored at the end of the planning horizon has an associated cost $cstock_{l,d,i}$ because they may not be required in the future and lose quality, or on the contrary, be used for the elaboration of products for which they were not intended, affecting the productivity levels of the plant. At the beginning of the planning horizon there is an initial inventory of logs available from previous planning periods, $stockini_{l,d,i}$.

2.3 Problem characteristics related to distribution activities

Regarding the distribution of the logs generated in the harvest areas, there is a heterogeneous truck fleet C to perform this activity. Each truck has a minimum and maximum load capacity ($capmin_c$ and $capmax_c$, respectively), therefore the quantity of logs to be transported will be limited by their corresponding weight, $weight_{l,d}$.

Each truck has a limited working day ($maxt_{c,t}$) and a maximum number of trips v, $v \in V$ to be completed in each period t. Each segment of the road network admits an average travel speed, which depends on whether the truck is loaded or unloaded. In turn, each truck has a stipulated loading and unloading time ($load_{c,f}$ and $unload_{c,i}$, respectively). Regarding the composition of the load, each truck can only transport logs of the same length per trip, allowing logs of different diameters to be loaded at the same time. Each truck is located at a regional base p, $p \in P$, from where its route begins and where it must end after completing all trips. The composition of routes presented in Bordón et al. (2018) [9] is considered in this work, where basically a route is made up of different types of movements.

The fixed cost for using a truck in a certain period is given by $ctruck_{c,p}$. The company cost policy considers a fixed cost (base) per use of trucks per period and a variable cost per kilometer traveled loaded and unloaded.

2.4 Optimization variables

The variables considered in this work are the following:

- The number of harvested stems and the number of stems left standing in each harvest area in each period, $Q^{CS}_{f,t}$ and $Q^{SS}_{f,t}$, respectively.
- The bucking patterns selection and the number of times they are used in each harvest area and in each period, $Y^{BP}_{b,f,t}$ and $Q^{BP}_{b,f,t}$, respectively.

- The number of generated logs of each type (length-diameter combination), per period, in each harvest area, $Q^{CL}_{l,d,f,t}$.
- The number of transported logs of each type, per period, from each harvest area to each plant, $Q^{TL}_{l,d,f,t}$.
- The inventory levels of logs of each type, per period, on the roadside in harvest areas, $Q^{RL}_{l,d,f,t}$.
- The number of processed logs of each type (above the minimum demand) in each plant in each period, $Q^{PL}_{l,d,i,t}$.
- The inventory levels of logs of each type, per period, in the storage yard of each plant, $Q^{SL}_{l,d,i,t}$.
- The truck selection in each period, $Y^{T}_{c,p,t}$.
- The type of loaded logs in each trip of each truck and the number of transported logs (of the same length but not necessarily the same diameter) on each trip of each truck from each harvest area to each plant in each period, $Y^{TT}_{l,c,v,f,i,t}$ and $Q^{TT}_{l,d,c,v,f,i,t}$, respectively.
- The route to be performed by each truck in each period, that is, its initial, loaded, unloaded and return movements, ($X^{D}_{c,p,f,t}$, $X^{L}_{c,v,f,i,t}$, $X^{U}_{c,v,i,f,t}$ and $X^{R}_{c,v,i,p,t}$, respectively).

The decisions listed above must be made seeking the minimization of the total costs (Z) related to harvesting and transport activities, guaranteeing the fulfillment of the demand of the plants and satisfying all the operative restrictions.

3 Mathematical model

The proposed MILP model is the following:

$$\min Z = CV^{Transp} + CF^{Transp} + CV^{Loss} + CV^{Stock} + CV^{Logs} \tag{1}$$

where,

$$CV^{Transp} = \sum_c \sum_{p \in PC_{p,c}} \sum_f \sum_t dpf_{p,f} cd_{p,f} X^{D}_{c,p,f,t} +$$
$$\sum_c \sum_v \sum_f \sum_i \sum_t dfi_{f,i} cl_{f,i} X^{L}_{c,v,f,i,t} +$$
$$\sum_c \sum_v \sum_i \sum_f \sum_t dif_{i,f} cu_{i,f} X^{U}_{c,v,i,f,t} +$$
$$\sum_c \sum_{p \in PC_{p,c}} \sum_v \sum_i \sum_t dip_{i,p} cr_{i,p} X^{R}_{c,v,i,p,t} \tag{2}$$

$$CF^{Transp} = \sum_c \sum_{p \in PC_{p,c}} \sum_t ctruck_{c,p} Y^{T}_{c,p,t} \tag{3}$$

$$CV^{Loss} = \sum_b \sum_{f \in BF_{b,f}} \sum_t closs_b loss_b Q^{BP}_{b,f,t} \tag{4}$$

$$CV^{Stock} = \sum_l \sum_d \sum_i cstock_{l,d,i} Q^{SL}_{l,d,i,t=|T|} \tag{5}$$

$$CV^{Logs} = \sum_l \sum_d \sum_f cqrl_{l,d,f} Q^{RL}_{l,d,f,t=|T|} \quad (6)$$

The objective function is given by the minimization of (1), where: (2) establishes the variable cost per traveled kilometer, (3) represents the fixed costs per use of trucks, (4) defines the cost for raw material loss when applying a certain bucking pattern, (5) sets the cost of keeping logs in plant storage yards at the end of the planning horizon, and (6) establishes the cost of not transported logs which remain on the roadside in the harvest areas at the end of the planning horizon.

The restrictions associated with the problem are the following:

$$qini_f = Q^{CS}_{f,t} + Q^{SS}_{f,t} \quad \forall f \in F, t = 1 \quad (7)$$

$$Q^{SS}_{f,t-1} = Q^{CS}_{f,t} + Q^{SS}_{f,t} \quad \forall f \in F, t > 1 \quad (8)$$

$$Q^{SS}_{f,t} \leq qend_t \quad \forall f \in F, t = |T| \quad (9)$$

$$Q^{CS}_{f,t} \geq qcsmin_f CUT_{f,t} \quad \forall f \in F, \forall t \in T \quad (10)$$

$$Q^{CS}_{f,t} \leq qcsmax_f CUT_{f,t} \quad \forall f \in F, \forall t \in T \quad (11)$$

$$Q^{CS}_{f,t} = \sum_{b \in BF_{b,f}} Q^{BP}_{b,f,t} \quad \forall f \in F, \forall t \in T \quad (12)$$

$$\sum_{b \in BF_{b,f}} nu_{l,d,b} Q^{BP}_{b,f,t} = Q^{CL}_{l,d,f,t} \quad \forall l \in L, \forall d \in D, \forall f \in F, \forall t \in T \quad (13)$$

$$Q^{BP}_{b,f,t} \geq qminb_b Y^{BP}_{b,f,t} \quad \forall (b,f) \in BF_{b,f}, \forall t \in T \quad (14)$$

$$Q^{BP}_{b,f,t} \leq qcsmax_f Y^{BP}_{b,f,t} \quad \forall (b,f) \in BF_{b,f}, \forall t \in T \quad (15)$$

$$Y^{BP}_{b,f,t} \leq CUT_{f,t} \quad \forall (b,f) \in BF_{b,f}, \forall t \in T \quad (16)$$

$$CUT_{f,t} \leq \sum_{b \in BF_{b,f}} Y^{BP}_{b,f,t} \quad \forall f \in F, \forall t \in T \quad (17)$$

$$CUT_{f,t} \leq CUT_{f,t+1} - CUT_{f,k} + 1 \quad \forall f \in F, \forall t \in T, k \geq t+2 \quad (18)$$

$$Q^{TL}_{l,d,f,t} + Q^{RL}_{l,d,f,t} = Q^{CL}_{l,d,f,t} \quad \forall l \in L, \forall d \in D, \forall f \in F, t = 1 \quad (19)$$

$$Q^{TL}_{l,d,f,t} + Q^{RL}_{l,d,f,t} = Q^{CL}_{l,d,f,t} + Q^{RL}_{l,d,f,t-1} \quad \forall l \in L, \forall d \in D, \forall f \in F, t > 1 \quad (20)$$

$$Q^{TL}_{l,d,f,t} = \sum_c \sum_v \sum_i Q^{TT}_{l,d,c,v,f,i,t} \quad \forall l \in L, \forall d \in D, \forall f \in F, \forall t \in T \quad (21)$$

$$Q^{TT}_{l,d,c,v,f,i,t} \leq qttup_{l,d,c,v,f,i,t} Y^{TT}_{l,c,v,f,i,t}$$
$$\forall l \in L, \forall d \in D, \forall c \in C, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (22)$$

$$\sum_l Y^{TT}_{l,c,v,f,i,t} = X^L_{c,v,f,i,t} \quad \forall c \in C, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (23)$$

$$\sum_l \sum_d weight_{l,d} Q^{TT}_{l,d,c,v,f,i,t} \geq capmin_c X^L_{c,v,f,i,t}$$

$$\forall c \in C, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (24)$$

$$\sum_l \sum_d weight_{l,d} Q^{TT}_{l,d,c,v,f,i,t} \leq capmax_c X^L_{c,v,f,i,t}$$

$$\forall c \in C, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (25)$$

$$\sum_c \sum_v \sum_f Q^{TT}_{l,d,c,v,f,i,t} + stockini_{l,d,i} = dmin_{l,d,i,t} + Q^{SL}_{l,d,i,t} + Q^{PL}_{l,d,i,t}$$

$$\forall l \in L, \forall d \in D, \forall i \in I, t = 1 \quad (26)$$

$$\sum_c \sum_v \sum_f Q^{TT}_{l,d,c,v,f,i,t} + Q^{SL}_{l,d,i,t-1} = dmin_{l,d,i,t} + Q^{SL}_{l,d,i,t} + Q^{PL}_{l,d,i,t}$$

$$\forall l \in L, \forall d \in D, \forall i \in I, t > 1 \quad (27)$$

$$Q^{SL}_{l,d,i,t} \leq maxstock_{l,d,i} \quad \forall l \in L, \forall d \in D, \forall i \in I, \forall t \in T \quad (28)$$

$$\sum_l \sum_d \left(dmin_{l,d,i,t} + Q^{PL}_{l,d,i,t}\right) \leq cap_{i,t} \quad \forall i \in I, \forall t \in T \quad (29)$$

$$\sum_t \left(dmin_{l,d,i,t} + Q^{PL}_{l,d,i,t}\right) = dtot_{l,d,i} \quad \forall l \in L, \forall d \in D, \forall i \in I \quad (30)$$

$$\sum_f X^D_{c,p,f,t} = Y^T_{c,p,t} \quad \forall (c,p) \in PC_{p,c}, \forall t \in T \quad (31)$$

$$\sum_v \sum_i X^R_{c,v,i,p,t} = Y^T_{c,p,t} \quad \forall (c,p) \in PC_{p,c}, \forall t \in T \quad (32)$$

$$X^D_{c,p,f,t} = \sum_i X^L_{c,v,f,i,t} \quad \forall (c,p) \in PC_{p,c}, \forall f \in F, \forall t \in T, v = 1 \quad (33)$$

$$X^L_{c,v,f,i,t} \leq Y^T_{c,p,t} \quad \forall (c,p) \in PC_{p,c}, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (34)$$

$$X^U_{c,v,i,f,t} \leq Y^T_{c,p,t} \quad \forall (c,p) \in PC_{p,c}, \forall v \in V, \forall f \in F, \forall i \in I, \forall t \in T \quad (35)$$

$$Y^T_{c,p,t} \leq \sum_v \sum_f \sum_i X^L_{c,v,f,i,t} \quad \forall (c,p) \in PC_{p,c}, \forall t \in T \quad (36)$$

$$\sum_f X^U_{c,v,i,f,t} \leq \sum_f X^L_{c,v,f,i,t} \quad \forall c \in C, \forall v \in V, \forall i \in I, \forall t \in T \quad (37)$$

$$\sum_i X^U_{c,v-1,i,f,t} \leq \sum_i X^L_{c,v,f,i,t} \quad \forall c \in C, \forall f \in F, \forall t \in T, v > 1 \quad (38)$$

$$\sum_f X^L_{c,v,f,i,t} = \sum_f X^U_{c,v,i,f,t} + X^R_{c,v,i,p,t} \quad \forall (c,p) \in PC_{p,c}, \forall v \in V, \forall i \in I, \forall t \in T \quad (39)$$

$$\sum_f \left(\frac{dpf_{p,f}}{vd_{p,f}}\right) X^D_{c,p,f,t} + \sum_v \sum_f \sum_i \left(\frac{dfi_{f,i}}{vl_{f,i}}\right) X^L_{c,v,f,i,t} +$$

$$\sum_v \sum_i \sum_f \left(\frac{dif_{i,f}}{vu_{i,f}}\right) X^U_{c,v,i,f,t} + \sum_v \sum_i \left(\frac{dip_{i,p}}{vr_{i,p}}\right) X^R_{c,v,i,p,t} +$$

$$\sum_v \sum_f \sum_i \left(load_{c,f} + unload_{c,i}\right) X^L_{c,v,f,i,t} \leq maxt_{c,t} \quad \forall (c,p) \in PC_{p,c}, \forall t \in T \quad (40)$$

$$CUT_{f,t}, X^D_{c,p,f,t}, X^L_{c,v,f,i,t}, X^R_{c,v,i,p,t}, X^U_{c,v,i,f,t}, Y^{BP}_{b,f,t}, Y^T_{c,p,t}, Y^{TT}_{l,c,v,f,i,t} \in \{0,1\} \quad (41)$$

$$Q^{BP}_{b,f,t}, Q^{CL}_{l,d,f,t}, Q^{CS}_{f,t}, Q^{KT}_{c,t}, Q^{PL}_{l,d,i,t}, Q^{RL}_{l,d,f,t}, Q^{SL}_{l,d,i,t}, Q^{SS}_{f,t}, Q^{TL}_{l,d,f,t}, Q^{TT}_{l,d,c,v,f,i,t}, Z \geq 0 \quad (42)$$

Restrictions (7) and (8) establish the balance of stems in each harvest area in each period (the number of stems that are cut and left standing at the end of the period). Constraints (9) determine the maximum number of standing stems at the end of the planning horizon. Restrictions (10) and (11) establish the minimum and maximum quantities of stems to be cut, by period, where $CUT_{f,t}$ is the binary variable that indicates whether the harvesting crew is cutting stems in the harvest area or not. Constraints (12) state that the number of stems cut in a given harvest area is equal to the number of times all cutting patterns are applied. In Equations (13) the quantity of logs of each type that is generated by using the bucking patterns is determined. Constraints (14) and (15) determine the minimum and maximum number of times that the bucking patterns can be applied, respectively. Restrictions (16) and (17) establish that a bucking pattern must be used in a harvest area during a period if and only if a harvesting crew cuts stems in the harvest area during that period. Constraint (18) ensures that harvesting crew cuts in successive periods. Restrictions (19) and (20) establish the balance of logs in each harvest area in each period. Equation (21) states that the logs transported from a harvest area to the plants in a given period must match the number of logs loaded on trucks in the same period. Constraint (22) determines the maximum number of logs of a certain length that a truck can transport on a given trip, while constraints (23) state that only logs of the same length can be loaded in one trip at a time. Restrictions (24) and (25) establish that the load of a truck must satisfy the conditions of minimum and maximum load capacity, respectively. Constraints (26) and (27) set the inventory balances of logs of each type in each plant. Constraint (28) determines the maximum inventory capacity of logs of each type in each sector of the storage yard, while restrictions (29) establish the processing capacity limit of each plant in each period. Equation (30) forces the total demand for each plant to be covered. Through the restrictions (31) to (40) the routes that each truck must perform are built, these constraints are based on the work of Bordón et al. [9]. Finally, (41) and (42) establish the nature of the variables involved.

4 Case study

In order to assess the capabilities of the developed model, a case study consisting of a sawmill that requires a certain number of logs of different types is considered. In Table 1 the minimum and total demands for a planning horizon of 5 days are shown. In addition, the total weight of the raw material demanded (in tons) is also presented. Assuming a conversion factor of 0.8 tons/m^3 of pine, in this illustrative example a weekly supply of more than 1,800 m^3 of raw material to a sawmill is considered. According to the last National Census of Sawmills [10], the volume of transported raw material in this illustrative example is equivalent to that handled in large companies (annual production level greater than 23,585 m^3, which means 471.7 m^3 per week approximately).

There are 3 open harvest areas with different stem availabilities to obtain the required logs: 8,000 stems in f_1, 7,000 stems in f_2 and 6,500 stems in f_3. In each

harvest area there are 2 assigned harvesting crews, which can use the bucking patterns presented in Table 2, where the percentage of material lost after applying a certain pattern is also presented (this loss of material can be seen in Fig. 1). Since each harvesting crew can process a maximum of 50 stems per hour, the maximum harvesting capacity is set at 100 stems per hour. In a similar fashion, if the harvesting crew performs the cutting activity, then it must work at least 50% of its capacity.

There is a truck fleet composed of 100 trucks with minimum and maximum capacity of 18 and 27 tons each, respectively. The fleet is distributed in 3 regional bases

Each truck can perform at most 3 loaded trips in its route, as long as the working time limit is respected (8 hours). Both loading and unloading times of each truck are 30 minutes. The distances between each node of the network are given by Table 3. The rest of the parameters used are omitted due to space reasons.

Table 1. Minimum and total sawmill demands.

Type of logs	Minimum demand per period					Total demand	Total weight (tons)
	t_1	t_2	t_3	t_4	t_5		
$l_1 d_1$	50	100	75	50	50	450	8.55
$l_1 d_2$	100	80	50	50	20	600	36.6
$l_1 d_3$	0	150	150	150	0	900	81.9
$l_1 d_4$	100	100	80	75	50	600	102
$l_2 d_1$	0	100	180	150	90	1050	23.1
$l_2 d_2$	200	120	100	80	120	900	63.9
$l_2 d_3$	150	300	150	200	0	900	95.4
$l_2 d_4$	100	150	250	150	150	1200	237.6
$l_3 d_1$	100	100	250	50	0	750	20.25
$l_3 d_2$	0	0	80	270	350	900	77.4
$l_3 d_3$	200	200	200	80	0	1050	135.45
$l_3 d_4$	0	0	80	250	220	900	216
$l_4 d_1$	100	300	100	0	0	600	18.6
$l_4 d_2$	0	0	150	250	100	600	61.2
$l_4 d_3$	80	80	80	100	200	750	114
$l_4 d_4$	120	120	120	120	0	600	169.8

Table 2. Bucking patterns applicable to each harvest area.

Type of logs	Bucking pattern (harvest area)									
	b_1 (f_1)	b_2 (f_1)	b_3 (f_1)	b_4 (f_2)	b_5 (f_2)	b_6 (f_2)	b_7 (f_2)	b_8 (f_3)	b_9 (f_3)	b_{10} (f_3)
$l_1 d_1$	2				1		1			
$l_1 d_2$							1			
$l_1 d_3$	2						1			
$l_1 d_4$	5						2	3		
$l_2 d_1$		1						1		
$l_2 d_2$						1				
$l_2 d_3$		2				1		1		
$l_2 d_4$		4				1	3	2	3	
$l_3 d_1$			1							
$l_3 d_2$					1				1	
$l_3 d_3$			1		1				1	
$l_3 d_4$			4		1	3			1	3
$l_4 d_1$				1						
$l_4 d_2$										1
$l_4 d_3$				1						1
$l_4 d_4$				3	2					1
losses (%)	19	10	13	11	5	8	10	13	12	11

Table 3. Distances between the nodes (in kilometers).

	f_1	f_2	f_3	i_1
p_1	100	80	95	35
p_2	80	30	150	55
p_3	45	105	65	40
i_1	50	110	85	

The model is implemented and solved in GAMS [11] 24.7.3 version, with the CPLEX 12.6.3 solver, in an Intel(R) Core(TM) i7-8700, 3.20 GHz.

The size of the considered case study is 30,565 binary variables, 73,461 positive variables and 114,122 equations. Following, the main results obtained after 15 minutes, reaching 0.87% of optimality gap, are detailed. It is worth highlighting that the model gives a lot of detailed information about the harvesting and log transportation planning, but due to reduced space in this presentation they cannot be shown and it is available for interested readers.

Regarding to the harvest stage, the number of stems cut in harvest area f_1 is 610, 570 and 770 in periods t_1, t_2 and t_3, respectively, while for the same periods the number of stems cut in f_2 is 800, 664 and 636, respectively. In the harvest area f_3 the

number of cut stems in periods t_1 and t_2 is 700 and 800, respectively, while in period t_3 no tree is harvested. There are no harvest activities in periods t_4 and t_5 in any harvest area. The bucking patterns used (and the number of times they are applied) in each period are detailed in Table 4.

Table 4. Bucking patterns used.

Period	Bucking pattern (harvest area)									
	b_1 (f_1)	b_2 (f_1)	b_3 (f_1)	b_4 (f_2)	b_5 (f_2)	b_6 (f_2)	b_7 (f_2)	b_8 (f_3)	b_9 (f_3)	b_{10} (f_3)
t_1	150	100	360	147		509	144		700	
t_2		180	390	453		31	180		200	600
t_3		770				360	276			

In Table 5 the evolution of demand levels by period and by diameter for a particular log length (l_2) is shown. In this table the level of minimum committed demand per period ("$dmin_{l,d,i,t}$"), the level of covered demand above the committed demand per period ("$Q^{PL}_{l,d,i,t}$") and the accumulated covered demand ("ACD") are detailed.

Table 5. Demand satisfaction.

Diameter	*Period*	$dmin_{l,d,i,t}$	$Q^{PL}_{l,d,i,t}$	*ACD*
d_1	t_1	0	0	0
	t_2	100	0	100
	t_3	180	0	280
	t_4	150	0	430
	t_5	90	530	1050
d_2	t_1	200	160	360
	t_2	120	0	480
	t_3	100	0	580
	t_4	80	120	780
	t_5	120	0	900
d_3	t_1	150	0	150
	t_2	300	0	450
	t_3	150	100	700
	t_4	200	0	900
	t_5	0	0	900
d_4	t_1	100	0	100
	t_2	150	0	250
	t_3	250	0	500
	t_4	150	260	910
	t_5	150	140	1200

Regarding the use of trucks, 13 vehicles are used in period t_1 (9 from p_2 and 4 from p_3), 7 in period t_2 (4 from p_2 and 3 from p_3), 9 in period t_3 (5 from p_2 and 4 from p_3), 5 in period t_4 (all from p_3) and 8 trucks in period t_5 (1 from p_2 and 7 from p_3).

As an example, the load of two of the trucks used in one of the planning periods (t_1) is presented in Table 6. In this case, both trucks perform 2 trips between harvest area f_1 and the sawmill. In this table, the composition of each load can be seen: number of loaded logs of each diameter (of the same length) and total weight of the load.

Table 6. Truck loads.

Truck/trip	*Log length*	*Diameter/#Logs*			*Total weight (tons)*
$c_{71}\, v_1$	l_2	d_2 : 137			26.95
$c_{71}\, v_2$	l_3	d_1 : 180	d_4 : 92		26.94
$c_{72}\, v_1$	l_2	d_1 : 100	d_3 : 50	d_4 : 98	26.90
$c_{72}\, v_2$	l_1	d_3 : 180	d_4 : 62		26.92

Logs inventory levels (length l_2) in both the harvest areas and sawmill are presented in Fig. 2 and Fig. 3, respectively. In Fig. 2, the blue, red, and green bars represent the number of logs on the roadside in harvest areas f_1, f_2, and f_3, respectively.

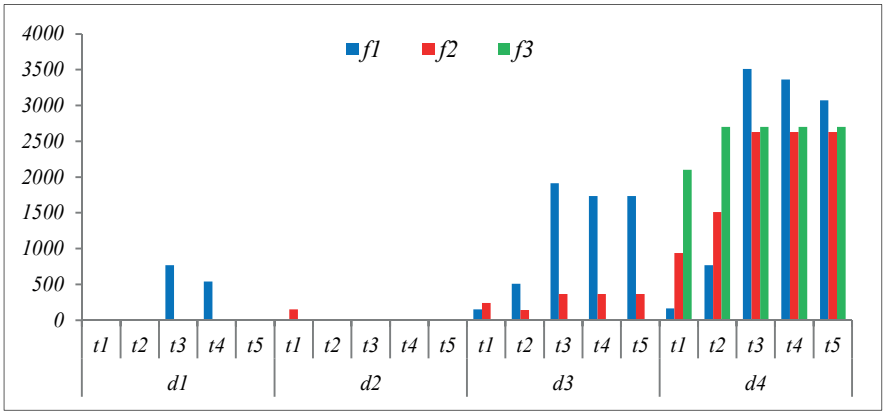

Fig. 2. Remaining logs of length l_2 on the roadside in harvest areas, by diameter.

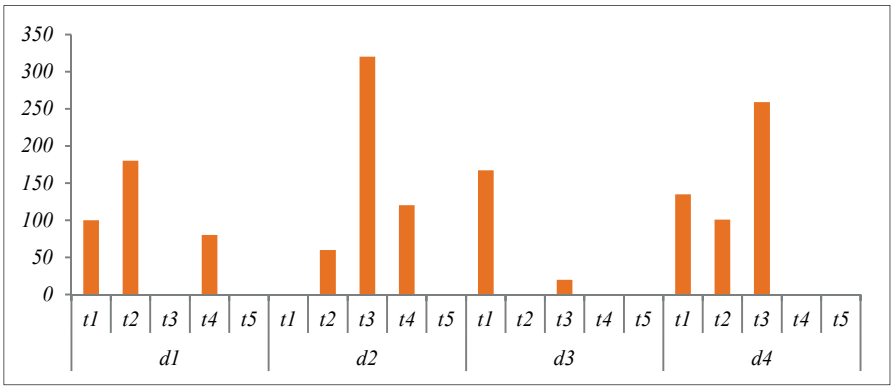

Fig. 3. Inventory level of logs of length l_2 in the sawmill, by diameter.

In Fig. 3 it can be seen that, since the logs stored in the plant at the end of the planning horizon are penalized, the model proposes a solution in which there are no logs (of any type) stored in period t_5.

Since the harvesting crews perform the logging activities during the first 3 periods in the harvest areas, in the last 2 periods the demand is satisfied with the logs stored (both in forests and plants). From the analysis of Fig. 2 and Fig. 3, it can be seen that in the last period, only logs that are required to fulfill total demand are transported, leaving the logs generated by excess on the roadside in harvest areas. This is mainly because, since more trucks will be required (at a higher cost), the model tends to use as few trucks as possible. Another factor influencing these decisions is that the cost of maintaining a log in the sawmill storage yard is slightly higher than the cost of maintaining the same log at the roadside in the harvest area.

5 Final remarks

In the forest industry, harvesting decisions are strongly related to plant production planning decisions. These plants, based on the commitments assumed with customers, plan detailed raw material supply programs to guarantee production. The harvesting crews receive these supply programs and harvest the raw material accordingly. Therefore, it is necessary to coordinate these efforts to avoid the generation of logs that will not be required by the plants and keep them in the storage yard at their respective cost. Transportation activities, in general, are not taken into account in this structure and have a great influence not only in the efficiency of the system but also in the cost structure.

The works found in the literature usually address these topics separately, which can lead to inefficient solutions. These inefficiencies are related to unnecessary logs inventory levels in both harvest areas and plants, and underutilization of truck loading capacity due to inefficient coordination, generating a high number of trips and a corresponding increase in the number of used trucks.

In this work, the proposed MILP model includes topics related to: vehicle routing, considering heterogeneous truck fleet, multiple periods, multiple plants and multiple depots; truck load composition; harvesting planning; and inventory management, both in harvest areas and plants.

The characteristics of the problem addressed and the solution time for the proposed example demonstrate the capabilities of the model to solve a problem in a weekly time horizon. Although the analyzed example was developed for illustrative purposes, it represents a situation in which more than 1,800 m^3 of raw material are transported, which in practice represents a situation related to large companies with a large supply flow. The model was solved with a CPU time limit of 15 minutes reaching a solution with an optimality gap equal to 0.87%.

Regarding the practical utility of the developed model, it can be used as a tool to support the planners' decisions, providing answers related to:: the periods in which the harvest teams must harvest, the level of forest production in each harvest area (number of generated logs of each type), the logs inventory levels, the number of trucks required to transport the harvested and the composition of each load, the route each truck perform in each period, the proportion of weekly demand covered in each period, among others. This solution capacity shows the potential of the developed MILP model when planning forestry activities.

Although the aim of this work is to present a mathematical model that jointly addresses issues that were not addressed before in the literature, key aspects emerge for improvement in future work, such as truck scheduling decisions to avoid or reduce waiting times that could be generated.

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Uniformidad en la distribución de aplicación de diferentes diseños de pastillas de pulverización

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Resumen. La aplicación de fitosanitarios se ha vuelto una herramienta fundamental en el proceso actual de producción agropecuaria. La misma es compleja y dominada por muchos factores. A fin de ayudar a reducir las pérdidas y maximizar la eficiencia se decide realizar un ensayo con 3 pastillas de pulverización(3D-Defy-XR11002VP-TXA8002VK) a 2,6 bar de presión, con 50 litros de tasa de aplicación y 17 km/h de velocidad, circulando con el botalón a 0,75m sobre bancos que simulan objetivos tridimensionales donde se colocaron tarjetas hidrosensibles. Se evaluó Densidad de impactos, DV0,5 y Eficiencia. Se obtuvieron valores mayores de todos los parámetros en los objetivos horizontales. Las pastillas con algún tipo de angulación antero posterior mejoraron la uniformidad de aplicación entre objetivos verticales. Las pastillas anguladas no mejoran las características de aplicación en objetivos verticales en comparación con el resto de las pastillas.

Palabras clave: Pulverización, Pastillas angulados, Calidad de aplicación.

1 Introducción

El actual modelo de agricultura adoptado en los diversos sistemas de producción, especialmente los extensivos, como algodón, soja, maíz, entre otros, es muy dependiente del uso de productos fitosanitarios que actúan como importante componente en el manejo de los cultivos.

La tecnología de aplicación de agroquímicos es un área multidisciplinaria que estudia aspectos referentes a la llegada del producto químico al objetivo a controlar. Es una de las etapas más importantes del proceso de producción agrícola ya que debe realizarse de forma adecuada para que permita la correcta colocación del principio activo en el cultivo, en el momento oportuno, en cantidad necesaria, de forma económica y con mínimo de contaminación a otras áreas [1]. [2] afirman que se busca obtener la máxima eficiencia del producto fitosanitario con el menor volumen de

caldo posible, convirtiéndose en una variable de gran importancia al momento de seleccionar las pastillas de pulverización.

Para disminuir el volumen de caldo y al mismo tiempo proporcionar la cobertura deseada en el objetivo, se puede reducir el tamaño de gota de una pulverización. Pese a esto, gotas muy finas poseen dificultades para depositar una cantidad adecuada de producto en el objetivo por ser más vulnerables a la pérdida por deriva y evaporación, en consecuencia proporcionan un menor control [3].

Por lo tanto, el volumen de caldo influye directamente en el nivel de cobertura del objetivo biológico, pero su aumento resulta en un mayor gasto de tiempo para el reabastecimiento de las máquinas aplicadoras, entre otros aspectos [4]. En algunos casos, un menor volumen de aplicación puede aumentar tanto la cobertura como la eficacia [5]. Las gotas más pequeñas tienden a tener una mayor afinidad por las superficies de las plantas, especialmente en los pastos debido a su orientación principalmente vertical [6] [7] pero esto no parece afectar la eficacia de los herbicidas. En el 56% de los estudios examinados por [8], una disminución en la tasa de volumen de la aplicación condujo a una mejora o a ningún efecto sobre la eficacia de los herbicidas. Esto es consistente con otros estudios realizados por [9] y [10]. Cambiar el tamaño de la gota de pulverización afectó la deposición, pero el efecto sobre la cobertura no alcanzó similares niveles de correlación [11] [12]. [13] realizaron varios estudios sobre el tamaño de gota en relación a la deriva y la eficacia del producto a aplicar; concluyeron que las gotas de mayor tamaño reducen la deriva potencial un 85%, mientras se mantiene o mejora la eficacia de aplicación.

Aunque no existe un rango de tamaño de gota específico que sea propenso a la deriva en todas las condiciones, muchos investigadores han considerado que tamaños de gotas menores a 75 μm [14], 100 μm [15], 150 μm [16] o 200 μm [17] son más propensas a la deriva. Por otro lado [18], mencionan que tamaños de gotas mayores a 400 micras también significan un problema para la aplicación, ya que sostienen que gotas de este tamaño no se mantienen sobre la superficie de la planta, a la vez que proveen de una baja cobertura sobre el objetivo.

[19] trabajaron en la evaluación de la penetración del asperjado con diversas pastillas en el control de roya de la soja. Concluyeron que la densidad de impactos producida por la pastilla cono hueco y un volumen de aplicación de 150 l ha^{-1}, fue significativamente superior del resto de las pastillas tanto en el estrato superior como en el inferior. Combinaciones de pastillas y caudales mostraron un comportamiento similar en el estrato inferior, sin diferencias significativas entre ellas, sin embargo mostraron un comportamiento inferior respecto al cono hueco a 150 l ha^{-1}. Para el caso de doble abanico, no obtuvieron una mayor penetración por debajo de los 20 cm superiores del follaje del cultivo. Las únicas pastillas con las que obtuvieron un número aceptable de impactos y aún mayores (50 gotas cm^{-2}), fueron las de cono hueco a 120 y 150 l ha^{-1}. Destacan que un mayor volumen de aplicación por sí mismo, no es garantía de un alto número de impactos dentro del follaje, sino que está relacionado con las características de las pastillas en cuanto al modo de generación de gotas. En el caso del cono hueco, el DVM (diámetro volumétrico mediano) estuvo por debajo del valor ideal de 200-250 μm mencionado por [20]. Los resultados obtenidos por este equipo

de investigadores muestran que las gotas finas generadas por estas pastillas fueron las que mejor comportamiento presentaron con respecto a la penetración.

Distintos autores han mencionado que los parámetros de calidad de aplicación se hallan relacionados también a los ángulos de incidencia del chorro de pulverización [21] [22] [23], [24].

Se considera que el ángulo de pulverización de 90° en relación al suelo (posición vertical) es el más frecuentemente utilizado [24]. Pese a ello, las pastillas que presentan abanico simple con ángulos hacia adelante o hacia atrás, simétricos o asimétricos se utilizan tratando de buscar mayor penetración y uniformidad de deposición en el cultivo. Todos los trabajos se refieren a la angulación anteroposterior de la pastilla de manera diferente. Para tratar de aclarar y mejorar la comparación entre trabajos se ha decidido tomar 90° como la posición vertical más común y los ángulos con valor positivos tomados desde la posición vertical (90°) hacia la dirección de avance y los valores negativos desde la posición vertical en sentido contrario a la dirección de avance.

[25], evaluó el ángulo de incidencia del abanico de pulverización de tres diferentes pastillas de abanico plano y uno con doble abanico plano, y encontró incrementos en la deposición del caldo de pulverización cuando utilizó el ángulo de +45° en relación con la vertical.

[26], encontraron en un ensayo con cortina de aire que una velocidad de aire superior a 25 m s^{-1} acoplada con un ángulo de chorro de aire de +20° y una pulverización fina aumenta tanto la cobertura de partes ocultas de las plantas como la penetración del rociado hacia el fondo del dosel.

Las características de mayor interés en las aplicaciones hidráulicas son proporcionadas por las pastillas, siendo de gran importancia conocer las peculiaridades de cada una, a fin de seleccionar la mejor alternativa para cada ocasión. Las pastillas, son el órgano responsable de la emisión de las gotas y, por lo tanto, son consideradas el componente más importante del equipo pulverizador, ya que determinan diversos factores relacionados a la calidad de la aplicación, es decir, proporcionan una distribución relativamente homogénea a lo largo del botalón (calidad) [27] y logran eficacia biológica en función de la cantidad de impactos/cm^{-2} depositados en el objetivo, siendo necesarios de 20-30 para herbicidas sistémicos, 30-40 para herbicidas de contacto y 50-70 para fungicidas e insecticidas. [28]

[22] explican que el espectro de gotas dependerá del diámetro del orificio de salida, el ángulo de pulverización de la pastilla y la presión de funcionamiento, factores que inciden sobre la calidad de la pulverización. Por lo tanto, la correcta elección de la pastilla es esencial para garantizar que los plaguicidas se apliquen de manera efectiva a la velocidad correcta.

[2] mencionan que muchas veces los fabricantes informan solamente si un modelo de pastilla es adecuado para un herbicida, insecticida o fungicida, considerando los modos de acción de contacto o sistémico.

Una forma de estimar la cobertura del objetivo puede ser a través del número de impactos por unidad de área. Buena parte de las recomendaciones técnicas de aplicación son basadas en este criterio, informándose un rango o un número mínimo de

gotas necesarias para un buen control. La deposición y cobertura pueden ser analizadas de diferentes formas, utilizándose objetivos naturales o artificiales.

Las tarjetas hidrosensibles son una herramienta que permite lograr aplicaciones eficientes y responsables. Son de papel, muy sensible a la humedad, que al entrar en contacto con gotas de agua o líquido, se manchan de color azul, revelando el lugar donde han caído las gotas.

Por lo tanto, teniendo en cuenta los pocos estudios que han explorado el efecto del tipo de pastilla y la angulación anteroposterior en las tasas de recuperación de producto y la calidad de deposición de pulverización en condición de barbecho se realiza un ensayo con el propósito de determinar la uniformidad de distribución y calidad de aplicación de pastillas con diferentes características generales y diseños de angulación anteroposterior sobre distintos objetivos.

2 Materiales y métodos

El ensayo se llevó a cabo en la Estación Experimental Julio Hirschhörn perteneciente a la FCAyF de la Universidad Nacional de La Plata 34°35 S, 57°57 W.

Se utilizaron las pastillas descritas en la tabla 1 con diferentes características de pulverización. Se trabajó a una presión de 260 kPa, con previo control del caudal de las mismas mediante jarra graduada, cronómetro y un caudalímetro electrónico, en condiciones semicontroladas dentro de un galpón sin viento y sin accidentes topográficos.

La máquina utilizada fue una pulverizadora Hatsuta, vinculada al tractor a través del elevador hidráulico de tres puntos (montada), con un tanque de 400 l de capacidad y un botalón con separación entre pastillas de 0,525 m.

El botalón pasó por encima de los objetivos de pulverización a una altura de 0,75 m a fin de uniformar la distancia de las pastillas según recomendación de los fabricantes para cada una ([29] [30])

Tabla N°1: Descripción de pastillas utilizadas.

Pastillas	Ángulo Anteroposterior	Ángulo de apertura	caudal	Tipo	Marca	Siglas
3D Defy	30*	100	02	Abanico	Hypro	Defy-3D
XR11002VP	0	110	02	Abanico	Teejet	AP
TXA8002VK	0	80	02	Cono Hueco	Teejet	CC

*Intercalada hacia adelante y hacia atrás sobre el botalón según indicaciones del fabricante (Pentair, 2017).

La evaluación se realizó con tarjetas hidrosensibles [31] colocadas sobre estaciones de medición de 0,5 m de largo por 0,15 m de ancho con 2 prismas rectangulares de diferentes dimensiones que funcionaron como obstáculo de las gotas para llegar a los diferentes objetivos (Imagen 1). Se colocaron dos estaciones de muestreo distanciadas a 0,75 m entre si y dos más como repetición, distanciadas a 2 m en la dirección de avance respecto de los anteriores (Imagen 2). Las tarjetas fueron dispuestas sobre las

5 caras de los prismas y dos adicionales, una por delante y otra por detrás del objetivo en forma inmediata y horizontal, como se visualiza en la Imagen 2.

Se utilizó un diseño experimental factorial de 3x2x7 completamente aleatorizado con 4 repeticiones. El primer factor estuvo representado por 3 diseños diferentes de pastillas (Tabla 1), el segundo factor fueron las 2 estaciones de medición [(obstáculos de diferentes dimensiones, (ver Imagen 1)] y el tercer factor las 7 posibles ubicaciones de las tarjetas en cada estación de medición (Imagen 2).

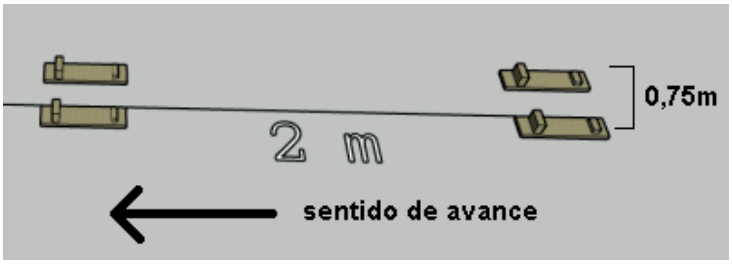

Imagen. 1. Distribución de las estaciones de evaluación.

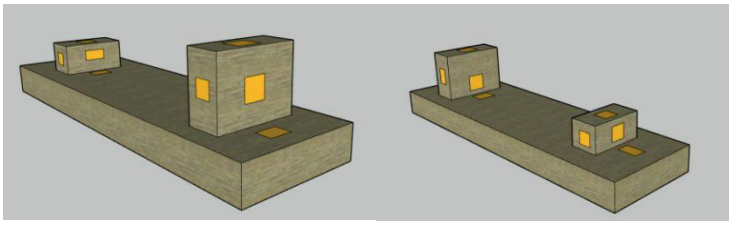

Imagen. 2. Disposición de las tarjetas hidrosensibles en el banco.

Luego del pasaje de la máquina pulverizadora se recogieron las tarjetas hidrosensibles y se colocaron en ambiente libre de humedad hasta su procesamiento. El mismo consistió en una digitalización de las tarjetas por medio de scanner cannon LIDE90 a 1200 d.p.i. y luego fueron analizadas con el programa CIR 1.5, obteniendo los siguientes parámetros que constituyeron las variables de respuesta:

- Densidad de impactos (N° de improntas cm^{-2}).
- Diámetro Volumétrico Mediano (DV 0,5 o DVM), (µm): Diámetro de gota que divide el volumen pulverizado a la mitad.
- Eficiencia (%): relación entre lo recogido en el objetivo y lo aplicado.

Para el análisis de uniformidad se procedió a dividir las tarjetas según cada posición, a fin de evaluar cuál de las pastillas consigue los mejores resultados en cada sector del objetivo y valorar de esa forma las características de la población de gotas que llegan a cada sitio.

Se realizó una segunda división de las tarjetas comparando los resultados de las que fueron colocadas en el objetivo más bajo del banco con las del objetivo más alto, analizando todas las pastillas en su conjunto con el fin de determinar la influencia de

la altura del objetivo. Asimismo, se analizó individualmente cada pastilla a fin de determinar la mejor alternativa frente a esta dificultad.

Esta forma de separación y análisis se realizó para objetivos verticales (V) y horizontales (H), objetivos delanteros (Ad) y traseros (Tr) y, por último, objetivos verticales laterales (D, I), verticales frontales y verticales traseros.

Debido a que las variables respuesta no responden a una distribución normal, los resultados fueron estudiados estadísticamente a través de un análisis de la varianza no paramétrico, mediante la prueba de Kruskal Wallis; y las medianas comparadas con un nivel de significancia ($p \leq 0.05$). Se utilizaron planillas Excel para el ordenamiento de los datos y para el análisis estadístico el programa INFOSTAT.

3 Resultados y discusión

Debido a que no se encontraron diferencias significativas entre los diferentes tamaños de obstáculos para ninguna de las variables estudiadas, se tomararon los resultados de ambos cubos como repeticiones.

3.1 Densidad de impactos

En la Fig. 1 se puede apreciar que la densidad de impactos que alcanza al objetivo tiene relación directa con su posición, los blancos horizontales siempre reciben mayor número de impactos independientemente de la pastilla utilizada, presentando como mínimo el triple de impactos respecto a los verticales. Esto puede deberse a su mayor superficie expuesta por su disposición perpendicular a la trayectoria teórica de las gotas tal como menciona [24]. La deposición por aspersión en objetivos verticales es difícil y varias investigaciones han demostrado que la misma disminuye cuando la orientación del objetivo cambia de horizontal a vertical [32] [33] [34].

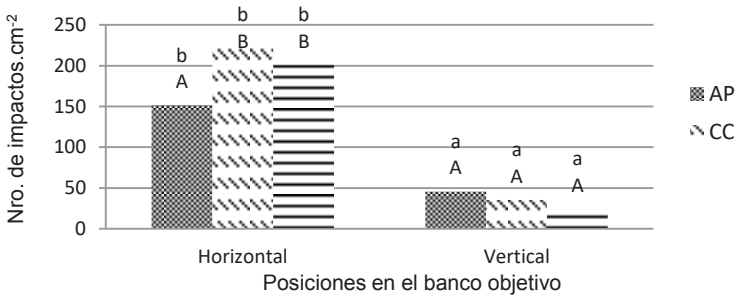

Fig. 1. Densidad de impactos cm^{-2} en función de los diferentes diseños de pastillas para las diferentes posiciones en el objetivo. Letras minúsculas diferentes sobre las columnas indican diferencias significativas entre posiciones y letras mayúsculas diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

CC y Defy-3D no presentaron diferencias significativas entre sí para las posiciones horizontales en ninguna de las ubicaciones (ver Fig. 2.) esto puede deberse al mayor número de gotas que generan estas pastillas en relación a AP ya qué las mismas generan gotas de tamaño fino en este rango de presiones mientras que AP genera gotas más gruesas (ver Fig. 6.).

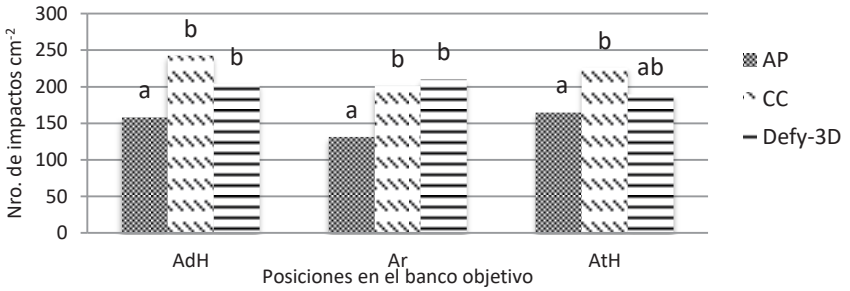

Fig. 2. Densidad de impactos.cm-2 para cada pastilla en función de la posición horizontal del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

Por lo tanto, podríamos suponer que la angulación de la pastilla tiene influencia en la proyección de las gotas tal como afirman [19] y [24]. Es decir, la angulación de la pastilla modifica la dirección con la cual la gota abandona la misma, y por consiguiente aumenta la posibilidad de alcanzar diferentes objetivos con disposición no horizontal, mejorando el comportamiento del abanico plano

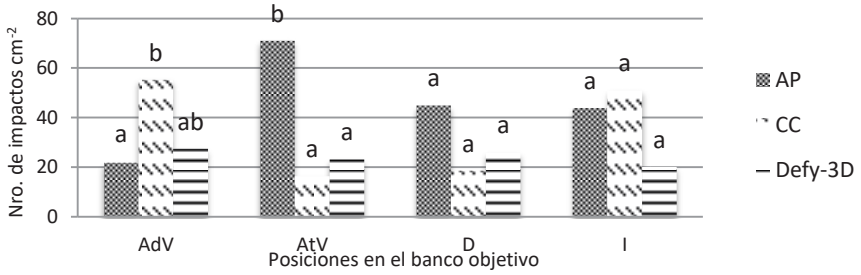

Fig. 3. Densidad de impactos.cm^{-2} para cada pastilla en función de la posición vertical del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

En las posiciones verticales, es interesante destacar el comportamiento de AP en la cara trasera vertical debido a que logro 300% más de impactos que las otras pastillas (Ver Fig. 3.). Esto puede deberse a la generación de un vórtice de viento por detrás del objetivo, lo que origina que las gotas cambien su trayectoria como consecuencia del aire circundante [35], las pastillas CC y Defy 3D al poseer una salida de gota angulada podrían sufrir menos este efecto.

En cuanto al CC fue notoria la cantidad de impactos alcanzados en la posición AdV, siendo ésta más del doble que las otras dos pastillas.

El comportamiento de Defy-3D fue regular en todas las posiciones verticales y nunca alcanzó el mayor número de impactos en relación a las otras dos pastillas, lo que puede deberse en parte, al efecto ejercido por la altura del botalón. [24] menciona, a partir de consideraciones teóricas, que la deposición sobre objetivos verticales se podría mejorar cambiando la trayectoria de pulverización desde la vertical estándar hacia un ángulo que sea más perpendicular al objetivo de pulverización. La aplicación de la teoría va a depender de si es posible retener tal ángulo desde la punta de la boquilla hasta el objetivo ya que a mayor ángulo mayor distancia debe recorrer la gota hasta el objetivo, siendo mayor el efecto de la gravedad sobre la misma y modificando de esta forma su angulación. [23] demuestran que a mayor altura del botalón, para todas las velocidades estudiadas, peor es la llegada de gotas a los objetivos verticales al igual que lo encontrado por [36].

Esto es de relativa importancia si se pretende realizar tratamientos con fungicidas o insecticidas ya que de utilizar el botalón demasiado alto seria dificultoso alcanzar el N° de impactos mínimos para control con pastillas anguladas, como se observa en el Fig. 3. Defy-3D no alcanzó los 30 impactos en ninguna de las posiciones verticals en tanto que, las demás pastillas no alcanzaron este N° de impactos en al menos una de las caras, lo que debería de ser considerado si el producto a aplicar posee una baja translocación en el vegetal. Esto nos permitiría afirmar que la angulación de la pastilla por sí sola no mejora el número de impactos obtenido en las posiciones verticales.

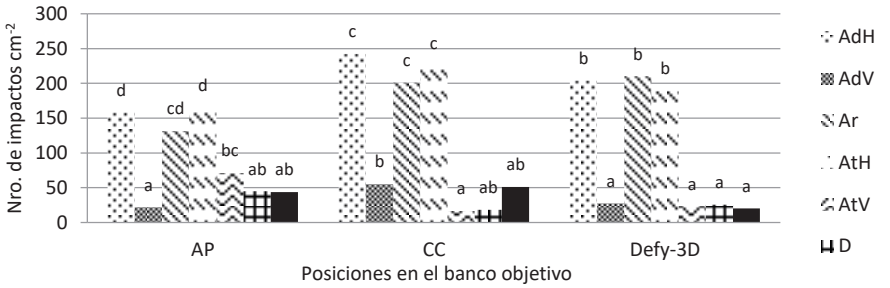

Fig. 4. Densidad de impactos en cada posición y ubicación del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre posición. Test de Kruskall-Wallis $p \leq 0,05$

En la Fig. 4, podemos observar el comportamiento de las pastillas en cada una de las caras del objetivo. Es posible apreciar a simple vista que los objetivos horizontales obtienen el mayor número de impactos independientemente de la pastilla utilizada, tal como se vienen mencionando. Por otro lado, es posible notar que ninguna pastilla logra una buena uniformidad en el número de impactos en todas las caras de los objetivos. Si se particionan los objetivos entre verticales y horizontales se observa que las pastillas Defy-3D son las de mayor uniformidad sin presentar diferencias estadísticas entre las posiciones verticales, al igual que con las horizontales. AP y CC son más variables y presentan diferencias estadísticas entre posiciones verticales pero no en las horizontales. Pese a esto, es posible apreciar una mayor uniformidad en las pastillas CC posiblemente pos su angulación tridimensional de salida de las gotas.

Esto nos permite concluir que la angulación de las pastillas posee un efecto positivo en la uniformidad de impactos para las diferentes caras de los objetivos pero sería recomendable ahondar en la investigación de esta variable para diferentes diseños y angulaciones de pastillas.

3.2 Diámetro volumétrico mediano (DV0,5)

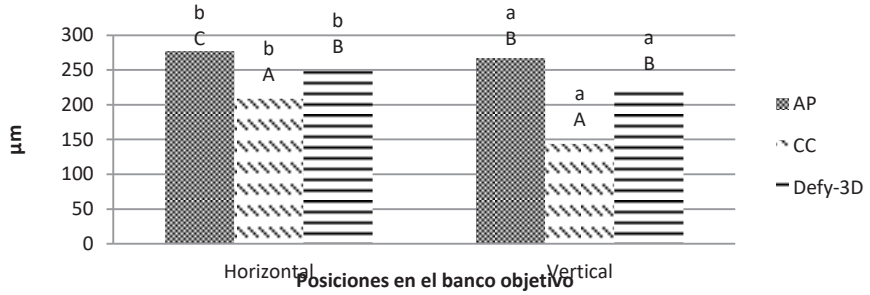

Fig. 5. DV0,5 en función de los diferentes diseños de pastillas para las diferentes posiciones en el objetivo. Letras minúsculas diferentes sobre las columnas indican diferencias significativas entre posiciones y letras mayúsculas diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

En la Fig. 5. se puede observar que en los objetivos verticales quedan retenidas gotas más finas respecto a los objetivos horizontales [26] [35].

[6] mencionan que las gotas más pequeñas parecerían tener más afinidad por los objetivos verticals, lo que se pueda deber a la menor influencia de la gravedad sobre ellas y su mayor tiempo de permanencia en el aire, lo que permite que pequeñas brisas las hagan impactar contra estos objetivos. En el caso de la pastilla CC es más notoria la tendencia, probablemente por ser la pastilla que genera las gotas más pequeñas.

Por otro lado, podemos observar que el tamaño de gotas que llega al objetivo mantiene una relación directa con el diseño de pastilla. Esto se puede deber a que diferentes diseños generan diferente tamaño de gota a una misma presión de trabajo pese a poseer idéntico caudal por minuto de erogación.

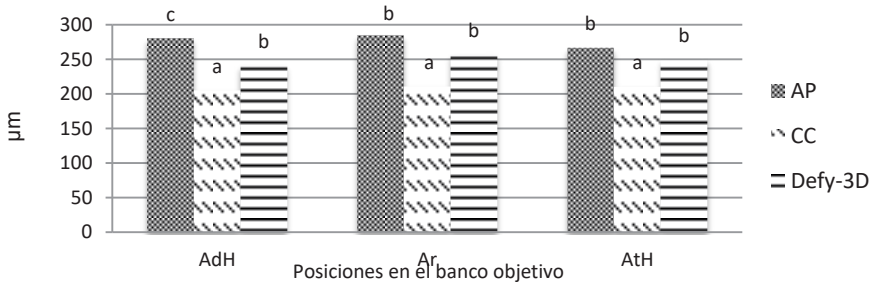

Fig. 6. Valores de DV0,5 para cada posición horizontal del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

A partir de los resultados mostrados en las Fig. 6. y 7. , se puede afirmar que AP es la pastilla que genera mayor tamaño de gotas sobre el objetivo, diferenciándose significativamente de CC en todas las posiciones, a excepción de AdV. Además, es de interés destacar que la pastilla Defy-3D nunca se diferenció significativamente de AP, lo que indica que el ángulo de proyección inicial de gotas tiene baja incidencia en el tamaño de gotas. Sólo en AdH e I la pastilla AP si se diferenció en el DVM que llega al objetivo, esto permitiría suponer que el tamaño de gota que llega a los objetivos horizontales está más relacionado con el tipo de pastilla y las condiciones ambientales que con la posición relativa del objetivo.

Las posiciones relativas verticales no son alcanzadas por el mismo tamaño de gota independientemente de la pastilla que lo genere, presentando diferencias de tamaño dentro de la pastilla y dentro de la posición. Para evaluar la homogeneidad de los DV0.5 en las diferentes posiciones y ubicaciones para cada diseño de pastilla, se calculó el coeficiente de variación (CV), donde AP obtuvo 23%, seguido por CC con 22% y Defy-3D con 18%. La pastilla Defy-3D presentó similar tamaño de gotas en las posiciones AdV y AtV y en las posiciones D e I, CC presentó la mayor desuniformidad en el tamaño de gotas para los objetivos verticales siendo que en las posiciones horizontales fue la pastilla con mayor similitud de tamaño de gotas. AP presentó diferencias marcadas entre AdV y AtV y similitud en sus posiciones D e I al igual que Defy-3D, pudiendo deberse a la angulación lateral de aproximadamente 5° para evitar que los abanicos se toquen en el botalón lo que genera que los mismos barran los objetivos D e I de forma similar.

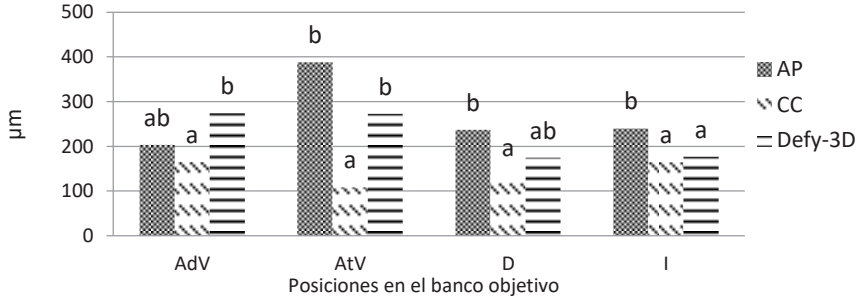

Fig. 7. valores del DV 0,5 para cada posición vertical del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

Por otra parte, se puede apreciar que generar gotas gruesas según [37], entre 340 µm y 403 µm, no significa producir bajo número de impactos en contra posición a lo expresado por [20]. Esto se obseva con la pastilla AP, que a pesar de generar gotas gruesas, logra un alto número de impactos en la posición AtV, obteniendo diferencias significativas respecto a CC y Defy-3D (Ver Fig. 7 y 3).

Según [37], tanto AP como Defy-3D, generan gotas medias y el CC gotas finas. Para CC se pudo observar en las posiciones verticales AtV y D un tamaño inferior a 150 µm que según [20], son más propensas a sufrir deriva. Mientras que AP y Defy-3D presentaron DVM por encima de los 170 µm en todas las posiciones y AP incluso

superiores a los 200 µm. Si consideramos que un adecuado balance se obtiene utilizando gotas entre 200-250 µm de diámetro estas pastillas podrían tener menores dificultades con la deriva en condiciones de campo con mayor viento

3.3 Eficiencia

La eficiencia es una variable de respuesta que depende del tamaño de la gota y del número de impactos que logran llegar al objetivo, esta se determina a partir de los litros ha^{-1} que llegan al blanco, respecto a los litros ha^{-1} erogados por el pulverizador. En el Fig. 8, se muestran los resultados de eficiencia para las distintas pastillas en las diferentes posiciones. Se puede visualizar que las mayores eficiencias se alcanzaron sobre las caras horizontales de los objetivos, independientemente del diseño de pastillas. Esto se debe a que las gotas tienen una mayor probabilidad de impactar sobre la mayor superficie expuesta en ese plano, logrando eficiencias mayores al 50% - 60 %. Esto además es acompañado por el mayor tamaño de los impactos que llegan a esta posición aumentando el valor de volumen recolectado (Ver Fig. 5).

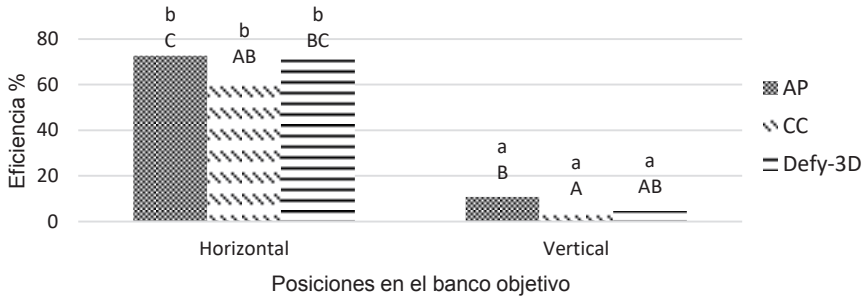

Fig. 8. Eficiencia en función de los diferentes diseños de pastillas para las diferentes posiciones en el objetivo. Letras minúsculas diferentes sobre las columnas indican diferencias significativas entre posiciones y letras mayúsculas diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

Como se observa en el Fig. 9., el comportamiento del CC fue homogéneo en todas las ubicaciones horizontales siendo la de menor eficiencia. La pastilla AP obtuvo un 20% más de eficiencia respecto al CC en las ubicaciones Ar y AtH, influenciado fundamentalmente por el DV0,5. Estos resultados concuerdan con lo determinado por [38] y [39], quienes afirman que aquellas pastillas que generan mayor tamaño de gota, generan mayores depósitos sobre el objetivo. Por otro lado, CC fue la pastilla que más uniformemente cubrió los objetivos llegando en forma similar a todas las ubicaciones a diferencia de AP y Defy-3D que en la posición AdH se asemejan a los valores de CC sin presentar diferencias estadísticas, pero que si se observan en Ar y AtH. Defy-3D nunca se diferenció de CC y AP permaneciendo en una posición intermedia entre ambas. Esto puede deberse en gran medida a que Defy-3D presenta un tamaño de gota

de llegada intermedio en casi todas las posiciones y una densidad de impactos también en una posición intermedia.

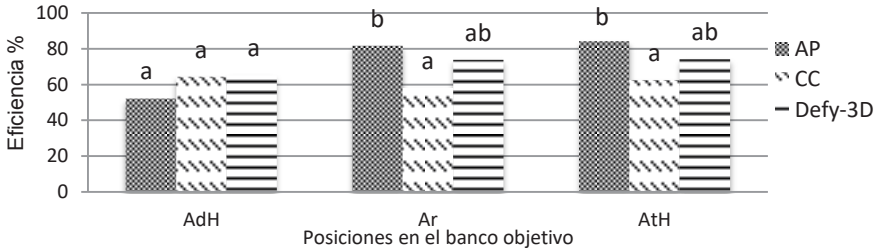

Fig. 9. Valores de Eficiencia para cada posición horizontal del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

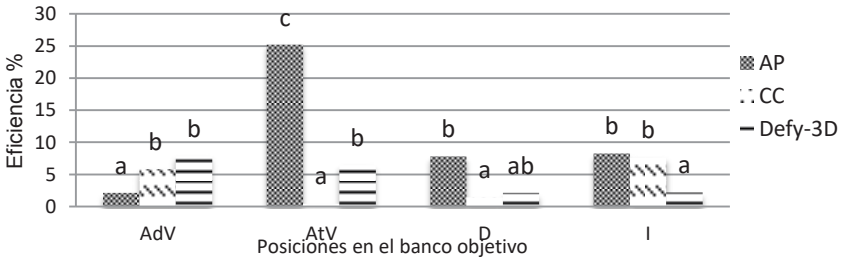

Fig. 10. Valores de eficiencia para cada posición vertical del objetivo. Letras diferentes sobre las columnas indican diferencias significativas entre pastillas. Test de Kruskall-Wallis $p \leq 0,05$.

Cuando los objetivos se disponían en forma verticals (Ver Fig. 10), solo la pastilla AP pudo superar el valores del 10%. Esto es importante de tener en cuanta ya que de ser necesario realizar controles sobre objetivos verticales será importante modificar parámetros de la aplicación que mejoren estos resultados.

4 Conclusiones

La angulación de las pastillas no mejora por si sola la calidad de aplicación en cuanto a Densidad de impactos y Eficiencia pero mejora la uniformidad de impactos entre las diferentes caras de los objetivos.

Conseguir la densidad de impactos para realizar controles biológicos en objetivos verticales reviste mayor complejidad que sobre objetivos horizontales.

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Evaluación del Endocarpio de Coco (Cocos Nucifera) como Sustrato en el Cultivo de Pleurotus Ostreatus en el Municipio de Villa del Rosario, Norte de Santander Colombia.

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Resumen. En el municipio de Villa del Rosario, Norte de Santander, empresas agroindustriales dedicadas al procesamiento de coco generan diferentes productos alimentarios, sin embargo el endocarpio del coco no es aprovechado, generando de 4 a 8 toneladas/semanales de residuo, ocasionando contaminación y proliferación de plagas. El Pleurotus ostreatus es un hongo comestible fácilmente cultivable a nivel mundial, rico en proteínas, vitaminas y minerales que crece en residuos con alto contenido ligno celulósico. Teniendo en cuenta la importancia nutricional del Pleurotus ostreatus y las condiciones ambientales favorables del municipio de Villa del Rosario, así como el alto contenido de compuestos ligno celulósicos que tiene el endocarpio de coco, se investigó el potencial de éste como sustrato para el crecimiento de Orellana (Pleurotus Ostreatus), evaluando las condiciones de crecimiento, variando el tamaño de partícula y los métodos de desinfección. Esta investigación se desarrolló en cuatro etapas, la primera consistió en determinar las características del endocarpio de coco; en la segunda se identificaron las condiciones óptimas de crecimiento de la Orellana (Pleurotus ostreatus); en la tercera se evaluó si el sustrato de coco proporciona las condiciones adecuadas para el crecimiento del hongo, en la última etapa se realizó el análisis de los resultados y la formulación de conclusiones. Con los resultados obtenidos, se demostró que bajo las condiciones ambientales de Villa Del Rosario, es posible cultivar el hongo Pleurotus ostreatus usando como sus-

trato el endocarpio de coco, realizando un tratamiento efectivo de desinfección y una reducción del tamaño de partícula al sustrato.

Palabras clave: Orellana, Endocarpio, Coco, Pleurotus ostreatus, Cocos, nucifera

1 Introducción

El coco es un fruto que se puede encontrar en la orilla de las playas tropicales arenosas del mar Caribe, océano indico y pacífico, este fruto tiene una demanda de uso agroindustrial para coco deshidratado, empleado en la panadería y repostería; del cual solo se aprovecha la pulpa que es la quinta parte de este y el resto de las capas fibrosas se desechan.[1]

En el área metropolitana de Cúcuta específicamente en el municipio de Villa del Rosario se encuentra ubicada la empresa Surticocos S.A.S, empresa dedicada a procesar 27.99 Toneladas/mes de coco, sin embargo, el endocarpio del coco no es aprovechado, generando de 4 a 8 Toneladas/semanal de residuo no aprovechados que ocasionan contaminación y proliferación de plagas.

El Pleurotus Ostreatus es un hongo fácilmente cultivable a nivel mundial encontrado en residuos lignocelulosicos, con altos componentes nutricionales. Teniendo en cuenta su importancia nutricional y sus requerimientos de crecimiento, se investigó si el endocarpio del coco es un sustrato adecuado para el crecimiento de Orellana (Pleurotus Ostreatus), evaluando sus condiciones de crecimiento, variando el tamaño de partícula del sustrato y el método de desinfección[2]

Esta investigación se llevó acabo en cuatro etapas, en la primera se determinó las características del endocarpio de coco; en la segunda etapa se identificaron las condiciones óptimas de crecimiento de la Orellana (Pleurotus Ostreatus); en la tercera etapa se evaluó si el sustrato de coco proporciona las condiciones adecuadas para el crecimiento del hongo y la cuarta etapa consistió en el análisis de los resultados y la formulación de conclusiones.

Demostrando que, bajo las condiciones ambientales de Villa Del Rosario, con un sustrato de endocarpio de coco, se puede cultivar el hongo Pleurotus Ostreatus realizando un tratamiento de desinfección del sustrato y una reducción del tamaño de partícula se permite obtener un cultivo de Pleurotus O. en endocarpio de coco.

2 Materiales y Métodos

El trabajo se enmarcó en una investigación cuantitativa con diseño cuasi-experimental con alcance descriptivo; debido a que se manipularon variables tales como el tamaño de partícula del sustrato de endocarpio de coco, métodos de desinfección del sustrato y se evaluó el crecimiento del hongo Pleurotus Ostreatus. [3]

2.1 Diseño experimental

Para la evaluación del crecimiento del hongo Orellana (Pleurotus Ostreatus), en un sustrato de endocarpio de coco (Cocos Nucifera). Se compararon las variables: método de desinfección respecto al tamaño de partícula, se realizaron 3 observaciones por tratamiento en un total de 12 tratamientos, en 3 ensayos realizados con las dos variables evaluadas. Para el ensayo 1 y 2 se evaluaron tres tamaños de partícula de (300, 600 y 118000 µm) versus tres métodos de desinfección (secado al sol, lavado en cal y choque térmico), finalmente el ensayo 3 se comprobó el crecimiento en sustrato de endocarpio sin triturar con tres tiempos de choque térmico.

2.2 Diseño metodológico.

Se pesó y separó la materia prima en cantidades de 10 kilos por tratamiento de desinfección, luego se realizó la adecuación de la materia prima para los procedimientos de pasteurización, lavado en cal y secado al sol, para los ensayos 1 y 2 evaluados. Más adelante se trasladó la materia prima a los laboratorios de operaciones unitarias en la sede de Campos Elíseos de la U.F.P.S. , el material se pasó por el molino de martillos de 5 hp y se tamizó consiguiendo tres tamaños de partícula (300µm, 600 µm, 118000 µm), se procedió a la adecuación del cuarto de cultivo, con lavado de pisos y paredes, se cubrió las entradas de luz y se realizó una aspersión para paredes con alcohol al 70% e hipoclorito al 10 %, se mezcló 700 ml de alcohol etílico (alcohol comercial de 96 °) con 300 ml de agua destilada o purificada, para la superficie de la mesa y lugar de inoculación, se mezcló 100 ml de cloro de uso casero con 900 ml de agua para los pisos y paredes del cuarto externo al del cultivo[4]; se realizó la inoculación del sustrato, más adelante se trasladó al cuarto del cultivo, controlando con termohigrómetro las condiciones ambientales de cada observación.

Reducción en los tamaños de partícula. Se realizó el diseño con base a las mallas de tamizador y a la potencia del molino de martillo de 5 hp, con tamaños de 300 micrómetros, 600 micrómetros y 118000 micrómetros además de los métodos de desinfección corresponden a un control, secado al sol, un choque térmico y lavado con cal como se puede evidenciar en tratamientos presentes de la Tabla 6. Tratamientos iníciales a evaluar, tamaño de partícula con método de desinfección.
Se agregó un tratamiento T10 en el ensayo 2 para determinar la necesidad de realizar una reducción de tamaño de partícula, y se planteó el ensayo 3, para determinar la necesidad de realizar una reducción de tamaño de partícula con un tratamiento térmico a diferentes temperaturas, como podemos ver en la Tabla 7. Tratamientos realizados en los ensayo 2 y 3.

Para la investigación se utilizó un arreglo factorial combinatorio (3 x 3), con trece tratamientos y tres repeticiones respectivamente evaluados en tres ensayos de cultivo. La inoculación se realizó en cada una de las bolsas de polipropileno de 0.5 kg, para los tratamientos del primer y segundo ensayo; en el tercer ensayo se utilizaron bolsas

de fique de 0.5 kg para permitir la aeración suministrando una sola vez durante todo el proceso 30 g de semilla por cada bolsa de 0.5 Kg de sustrato evaluado [5]

Tamizado. En este proceso se utilizó un tamiz de 300µm, 600µm y 118000 µm con un sistema de vibración por 3 minutos, a una itinerancia de 3segundos y una amplitud de 0.5mm. [10], con un tamizador ANALYSETTE 18 marca Fritsch GmbH.

Tratamiento de desinfección o esterilización de los sustratos. Para utilizar los sustratos en el cultivo del hongo seta, es necesario someterlos a un tratamiento previo, que consiste básicamente en aplicarles calor para disminuir la flora microbiana nociva que está presente en ellos y de esta manera evitar que los microorganismos compitan por espacio y nutrientes con el micelio de Pleurotus. [6]

Secado al sol. Todos los residuos fueron seleccionados y sometidos a un proceso de secado mediante la exposición directa al sol hasta que se observaran físicamente secos.

Tratamiento con choque térmico. El sustrato, se remojó en agua caliente y limpia, a 70-80°C, durante 15 minutos. Se realizó un par de aclarados o lavados más con agua caliente, hasta que los líquidos salientes fueron claros. Éste sistema es rápido, humedece y pasteuriza al mismo tiempo, no necesita vapor u otra manipulación por separado. Durante el remojado, el sustrato suele tomar 3 a 4 veces su peso en agua. [7]

Inmersión en agua alcalina. Esta es una de las técnicas más recientes que se practican en el cultivo de hongos. La desinfección con cal es un proceso propuesto como una alternativa, en la que se utiliza agua alcalinizada con cal comercial [Ca (OH)2], destruyendo de esta manera semillas, insectos, parásitos, hongos y bacterias, que pueden contaminar el sustrato y que pueden competir con el hongo de interés. Se trata de sumergir el sustrato en agua alcalinizada con cal comercial durante cierto tiempo dependiendo del sustrato y de las condiciones ambientales del lugar de cultivo. Según estudios realizados en México, la concentración y el tiempo adecuado para la preparación es de 0.5 % durante 24 horas respectivamente, en donde se alcanzó una alta eficiencia biológica. Esta técnica tiene una gran ventaja sobre las otras por ser un método en frío, alternativa para evitar el uso de altas temperaturas y por lo consiguiente un gasto energético. [8]

Traslado de la materia prima al área de siembra. La fase experimental se llevó a cabo en un cuarto cerrado, paredes de plástico y piso de tableta, con dimensiones de: 3m x 3 m y una altura de 2,10 m. Se lavaron las paredes y el piso con hipoclorito de sodio a 20 ppm. Para obtener las condiciones requeridas por el Pleurotus, se cubrió la ventana con plástico negro al 70%, manteniendo condiciones de luz y temperatura; para asegurar la humedad adecuada se realizaron riegos con una frecuencia de tres veces al día. Las variables fueron monitoreadas diariamente con un termohigrómetro.

Inoculación con la semilla de Orellana. Se realizó la inoculación de la semilla, en el municipio de Villa del Rosario Colombia, con los tres tipos de tratamientos de desinfección y tres repeticiones de cada tamaño de partícula. En el caso de los tratamientos para el endocarpio del coco se usó 0.5 kg de sustrato, implementado un inoculo de 20 g. de semilla por bolsa. La muestra de secado al sol se usó como muestra patrón vs las que llevan tratamiento de desinfección. La siembra se realizó en un lugar cerrado y aislado de plagas, con suelo en cemento y desinfectado, como se indica en la literatura. Para la desinfección de la sala de siembra y herramientas, se usó hipoclorito de sodio al 5 % diluido en agua (0.5 litros de hipoclorito en 20 litros de agua) [9]; se inocularon muestras de 500 gramos (g) peso húmedo de sustrato desinfectado de endocarpio de coco con 20 gramos semilla de Orellana, esta etapa de la investigación se realizó con elementos de protección como guantes de látex, tapabocas, cofia, lentes de seguridad, botas y overol, para disminuir la probabilidad de impactos negativos en inocuidad del hongo.[10]

Traslado al área de crecimiento. En esta etapa se realizó la adecuación del área para poder llevar las muestras inoculadas, al espacio conforme con los requerimientos técnicos para el crecimiento de Orellana. De acuerdo a las indicaciones, el principal requisito del área es ser anaerobia, por lo que no puede estar sometida a ningún tipo de alteración del ambiente del cuarto, como exposición a luz solar, humedad relativa y temperatura y la temperatura, la medición del ambiente se hizo con ayuda de un termohigrómetro que valoró en tiempo real los factores mencionados anteriormente. Además, se realizaron unos ligeros cortes en los costados de la bolsa que permitieron que los carpóforos crezcan de una manera uniforme, además de monitorear fácilmente la cantidad el tamaño, peso, color y tiempo de maduración que determina el rendimiento biológico del sustrato.[5]

Cuarto de fructificación. En esta etapa las muestras fueron dispuestas en un área limpia y desinfectada con sello de hermeticidad para impedir la entrada de plagas y así poder mantener controladas los factores de temperatura, humedad relativa y exposición a luz solar, en este paso se permitió el ingreso de luz solar de manera controlada y de forma indirecta con el propósito de posibilitar el crecimiento de la seta, ya que de exponer demasiado a esta luz puede afectar el cultivo y marchitarse.

3 Resultados.

3.1 Resultados de la caracterización físico-química del endocarpio de coco

Los resultados obtenidos de las pruebas de laboratorio del endocarpio de coco usado como sustrato en el cultivo de Pleurotus Ostreatus se presentan en la Tabla 1. (Pruebas Fisicoquímicas y Bromatológicas).

Tabla 1. Pruebas Fisicoquímicas y Bromatológicas.

Prueba	Método	Resultados
Humedad	A.O.A.C. 1925.10.- estufa	5.5%
Fibra detergente neutron	A.O.A.C. 15th Edition 1990. Gravimetría	79.67 %
Fibra detergente acida	A.O.A.C. 973.18. gravimetría	68.78 %
Hemicelulosa	Diferencia de FDN Y FDA	10.89%
Celulosa	A.O.A.C. 15th Edition 1990. Gravimetría	24.37%
Lignin	Diferencia de CELULOSA Y FDA	44.41%
Ceniza	A.O.A.C. 942.05	1.25%
Nitrógeno total	Manual de técnicas Analíticas MRE-001	0.29%
Determinación de pH	Portable pH meter	6.50

Fuente: Los resultados de la Tabla 1, fueron obtenidos por los autores, a partir de la caracterización del endocarpio del coco.

3.2 Resultados para la identificar las condiciones adecuadas de crecimiento de la Orellana (Pleurotus ostreatus)

El cultivo de hongos de manera artesanal, a bajo costo (por sus características de austeridad), por lo general ejerce poco control sobre las condiciones del medio (Temperatura, humedad, ventilación, luz, oscuridad, etc.). Los cultivos son más estables y más productivos cuando el lugar de cultivo posee aire acondicionado. Sin embargo, las condiciones de cultivo caseras son baratas, dependientes de las condiciones del ambiente natural y son productivas a bajo nivel, suficiente para autoconsumo y comercialización del excedente. La temperatura se puede regular abriendo ventanas y puertas (si es que existen) para que la temperatura baje y permita además una ventilación.[11]

Los resultados obtenidos en la presente investigación, están descritos en la Tabla 2. Condiciones promedio de crecimiento de la investigación en el cultivo del Pleurotus Ostreatus, en un sustrato de endocarpio de coco en endocarpio de coco.

Tabla 2. Condiciones promedio de crecimiento de la investigación en el cultivo del Pleurotus Ostreatus en un sustrato de endocarpio de coco en endocarpio de coco.

Cultivo	Variables p				
	Temperatura °C	Humedad %	pH	Días de colonización	Días de aparición de carpoforos
Ensayo 1	27-34	63-98	6.41	12	14
Ensayo 2	23- 28	80-99	6.41	10	40
Ensayo 3	17-20	95-99	6.43	16	-

Fuente: Resultados obtenidos por los autores.

Realizando una revisión de antecedentes en investigaciones similares, se pudo encontrar temperaturas de incubación y fructificación, que permitieron comparar los resultados obtenidos en la presente investigación, los datos encontrados se muestran en la Tabla 3.

Tabla 3. Temperaturas de incubación y fructificación obtenidas en investigaciones similares.

Temperatura incubación °C	Temperatura fructificación °C	**A**utor
24-25	18-23	Ardon, 2015
26 ± 3	15 ± 3	A. Sánchez et al., 2013
26 ± 2	26 - 28	Romero et al., 2010
20- 28	23 - 24	Bejarano, 2016

Fuente: Compilación de los autores a partir de las referencias citadas [6, 11, 18]

La humedad se puede regular aplicando agua al suelo (esto permite también regular la temperatura), en cuanto a la humedad relativa del cuarto de fructificación debe estar entre el 80 y el 95%, dependiendo del desarrollo del cuerpo fructífero (por lo que se recomienda tener un termohigrómetro en el cuarto de cultivo para su monitoreo). La humedad en el cuarto puede ser ajustada mediante el riego con agua, durante algunas horas del día y así evitar que el sustrato se reseque. Al aparecer los primordios, la humedad relativa del cuarto de fructificación debe disminuirse a 85% - 90% y aumentarse la frecuencia de riego dependiendo de la tasa de fructificación. Durante el período de cosecha una humedad relativa entre el 80 y el 85% garantiza una calidad satisfactoria en el hongo.

3.3 Resultados de la evaluación el crecimiento del hongo (Pleurotus Ostreatus) en el endocarpio de coco (Cocos Nucifera), como sustrato para determinar la viabilidad de este nutriente en la producción de hongos comestibles

Se evaluaron las condiciones óptimas de crecimiento del hongo en los tres ensayos, para identificar que tratamiento presenta mayor viabilidad; sin embargo la producción de P. ostreatusse presentan pérdidas debido a contaminación en el sustrato mal desinfectado, causadas por hongos, bacterias, virus e insectos, que en su mayoría atacan en los primeros días del cultivo disminuyendo así la producción[7].

Resultados Ensayo 1, evaluación del cultivo de Orellana en dos tratamientos de desinfección vs tres tamaños de partícula. En las condiciones ambientales de Villa del Rosario se pude obtener un cultivo de Orellana con buena respuesta de crecimiento, se ve afectado por la contaminación de insectos que invade la muestra de la T1, T2 Y T3, que no muestra presencia de micelio o invasión del hongo ya que la cantidad de insectos en las muestras se propagaron a los otras tratamientos y repeticiones.

El tratamiento T4 con 4 repeticiones fue el de mejor aceptabilidad del hongo con un periodo de invasión de 12 días y de crecimiento en 17 días, las condiciones de humedad de este tratamiento fue de 8% y una temperatura de 31.5°C.

Comparados con los resultados de T4 las los tratamientos T1, T2 Y T3 con las condiciones ambientales de humedad (85-95%) y temperatura (26 – 32 °C), se evidencia que la plaga impide el crecimiento o propagación del hongo en el sustrato, por lo cual es necesario realizar un método de desinfección que destruya tanto larvas, pupas y mohos en el sustrato.

El resultado de la investigación para el primer ensayo demostró que el Pleurotus ostreatus crece en las condiciones ambientales de Villa el Rosario, con un tamaño de partícula de 0.600 mm, utilizando un tratamiento de desinfección de choque térmico correspondiente al tratamiento T4. El cuerpo fructífero murió con un tamaño aproximado a los 8 cm de largo y 5 cm de ancho.

Resultados Ensayo 2, evaluación de 3 métodos de desinfección: secado al sol, choque térmico e inmersión alcalina. Para el ensayo 2, se evaluaron tres métodos de desinfección del sustrato: secado al sol, choque térmico e inmersión alcalina, con una variación del tratamiento secado al sol en el que no se trituró el sustrato (T10) y los tratamientos de T4 a T9 se realizaron con 3 tamaños de partícula, para realizar el montaje, se trasladó el cuarto de cultivo a otro sitio en Villa del Rosario donde la temperatura ambiente fue de 23°C y una humedad de 87%.En este ensayo se encontró una invasión del micelio en un tiempo de 5 a 6 días.

Pese a las condiciones del cultivo para el ensayo dos, las muestras compitieron por el sustrato (Trichoderma spp., Penicillium spp., etc. Según la literatura) impidiendo que posteriormente el desarrollo del Pleurotus Ostreatus. La pasteurización así realizada no proporciona una protección natural del substrato contra las contaminaciones fúngicas, especialmente si se trata de Trichoderma spp.[12]

Los tratamientos de T4 A T10, presentaron contaminación a las dos semanas de la inoculación y la presencia de hongos competentes por el sustrato separamos las muestras contaminadas para obtener una hipótesis alternativa.

Se observó presencia de moho contaminante en el tratamiento T6 del ensayo 2. Los primordios empezaron a crecer, el tratamiento y sus repeticiones se separaron, se dejó

aislado para observar su crecimiento y compararlo con las muestras aun no contaminadas, luego de 51 días los carpoforos alcanzaron tamaños de 5 a 7 cm. De altura y 5cm de ancho.

Se realizó un Ensayo 3, en el que se evaluó el crecimiento del hongo en el endocarpio de coco sin triturar, desinfectado con el método de choque térmico durante 20, 30 y 40 minutos, las condiciones ambientales de crecimiento fueron de 17°C y humedad de 99%.

4. Análisis de Resultados

4.1 Caracterización del sustrato

Resultados de celulosa. Todo material ligno-celulósico está constituido por tres componentes: celulosa, lignina y hemicelulosa [13]. Se conocen más de 200 sustratos posibles para el cultivo de Pleurotus ostreatus, estos están principalmente compuestos por celulosa (45 a 60%) hemicelulosa (15 a 20%) y lignina de (10 a 30%).

Comparado con la cantidad de celulosa con 24.37% es el compuesto que más degrada el hongo para su desarrollo al presentarse en menor cantidad puede afectar los resultados de la investigación.

Una de las mejores fuentes de carbono para el crecimiento miceliares es la celulosa para el desarrollo óptimo del hongo [14].

Lignina. El porcentaje de lignina encontrado en el endocarpio de coco mostro que su cantidad 44.41% está en mayor presencia que la celulosa 24.37%, como muestran otros estudios donde el nivel de lignina no supera el 15% tomando lo descrito.

La degradación de componentes estructurales está estrechamente relacionada con la naturaleza química de los sustratos y la capacidad de degradación enzimática del hongo [15]. Lo anterior coincide con estudios similares, donde los mejores resultados, están asociados a sustratos que tienen un alto contenido de lignina [16].

La cantidad de hemicelulosa y celulosa en los resultados de la presente investigación, son 10% menor a la de Bledzki (2010) [17], con respecto a la fibra la cantidad de FDN la presente investigación solo tuvo una diferencia de 2.33% .El FDA de éste estudio es menor a un 7.78% comparada con la de autores.

En la investigación de Rivera (2013) [14] se sustenta que el hongo en su fase de crecimiento micelial (fase de incubación), consume preferiblemente carbohidratos solubles y hemicelulosa respecto de la celulosa y lignina. Con base en esto, el sustrato de endocarpio de coco no proporciona suficientes carbohidratos solubles, asimilables por el hongo en su fase de crecimiento en cuanto al contenido de hemicelulosa pero si en cantidades de lignina.

El resultado de nitrógeno de 0,29%, puede considerarse bajo para la obtención de una mayor eficiencia biológica y el contenido de proteína en el hongo. Se considera que para el cultivo del hongo Pleurotus el contenido de nitrógeno puede estar entre 0,7-0,9 % en peso seco [12].

Todos los alimentos, cualquiera que sea el método de industrialización al que hayan sido sometidos, contienen agua. La determinación del contenido de humedad, es uno de los análisis más importante y ampliamente usados en el proceso y control de

los residuos, ya que indica la cantidad de agua involucrada en la composición de los mismos [18]. Según el contenido de humedad de la biomasa es la relación de la masa de agua contenida por kilogramo de masa seca, el polvo de coco es altamente higroscópico, tiene una capacidad de retención de agua de hasta cuatro veces su peso, elevada capacidad de retención de agua facilita tener disponible el agua necesaria para el cultivo, suficiente suministro de aire, distribución del tamaño de las partículas adecuado para mantener las condiciones anteriores [19], esta capacidad de retener agua en el sustrato asegura que el ambiente de crecimiento para el hongo sea adecuado con un porcentaje de 5.5% en base seca.

En cuanto al efecto del tamaño de partícula sobre la capacidad de aireación y el agua total disponible, se estudiaron sustratos preparados con diferentes proporciones de partículas menores de 1 mm de diámetro; se determinó que conforme se incrementa el porcentaje de partículas menores de 1 mm, la capacidad de aireación disminuye. Por esto el sustrato con un rango de tamaño de partícula en los tratamientos de 0.300 y 0.600 μm, se compactó, debido a la cantidad de humedad en el sustrato por la formulación aplicada.

4.2 Identificación de condiciones de crecimiento del hongo

Comparado con los estudios de Bejarano (2016) [18], la temperatura óptima para el cultivo de Orellana es de 20-28°C y humedad de 70 a 80%, valores en los cuales el hongo alcanza sus mejores valores de crecimiento y fructificación. Las condiciones de crecimiento fueron las adecuadas durante el cultivo con parámetros ambientales de la región, Con temperaturas promedio de 26-28°C, estos parámetros indican que en temperaturas ambiente de 25 a 28°-C se pueden obtener resultados positivos para la siembra de pleurotus ostreatus.
Según Fernandez (2004) [20], no existe una única fórmula para la producción de Orellanas, esto es determinado por el mercado a quien va dirigida y la biomasa presente en el lugar donde se plantarán. De los tantos sustratos utilizados se tienen datos de que mientras más rico sea el sustrato más susceptible es para contaminarse por estas razones asegurar un método de desinfección adecuado y buenas prácticas de manejo. Las condiciones de cultivo de este estudio fueron 23-26°C y humedad de 90-99%, con una producción a los 15dias para el bagazo de caña, 23 días para el heno, luego a los 18 días en el tratamiento de cacao y seguidamente aparecieron los primordios de la combinación de cacao, maracuyá y bagazo de caña a los 20 días. El tratamiento que pasados 20 días no mostro ninguna respuesta en relación con el hongo Pleurotus ostreatus es el de cáscara de maracuyá.

Las condiciones de temperatura fueron de 26-28°C y una humedad de un 70-80%, las muestras correspondientes a los sustratos de pajilla de frijol y rastrojo de maíz, no desarrollaron fructificaciones en este periodo, sus estadios requirieron más de 28 días de incubación y 3 días más para su etapa adulta. El periodo de producción total más corto fue de 63 días en el sustrato de paja de trigo, en cebada fue de 68 días, en el sustrato de la hoja de plátano fue de 72 días, en el rastrojo de maíz 84 días y el mayor periodo de producción lo obtuvo la pajilla de frijol con 95 días, con un total de 3 co-

sechas por sustrato. Indicando que la producción del hongo se ve afectada en el desarrollo por las temperaturas, pero que si llega a una etapa de fructificación.

De acuerdo con Donado (2014) [21], las especies de Pleurotus tienen fototropismo positivo, ya que la luz (intensidad luminosa, fotoperiodo y tipo de radiación), es uno de los factores necesarios para el desarrollo de los primordios. En condiciones de total oscuridad se diferencian escasos basidiocarpos que suelen ser deformes, racimos, de forma coraloide, color blanco y sabor amargo, en los que no se distingue el pie y el sombrero. En condiciones de escasez de luz, se asiste a la producción de cuerpos fructíferos con forma de corneta, sombrero muy reducido y pie alargado y débil.

4.3 Evaluación de las condiciones de crecimiento del hongo

Aunque las condiciones de crecimiento estuvieron dentro de los valores de la literatura las variables de temperatura para el cultivo del hongo no pueden dejarse al azar, deben controlarse lo más posible para asegurar una estabilidad en el cultivo, ya sea por medio de instrumentos básicos como atomizadores o instalando sistemas de riego y así evitando la contaminación cruzada por parte de los operarios del cultivo.

Otro factor importante en las condiciones de crecimiento es una semilla que asegura un rendimiento de propagación mayor al 90%, se recomienda inocular in vitro para posteriormente inocular el sustrato de estudio.

Para evitar problemas de contaminación en el cultivo del hongo ostra, es necesario trabajar en condiciones asépticas, realizando una buena esterilización y pasteurización de los sustratos, desinfección de los cuartos de incubación y fructificación, esto ayuda a evitar la proliferación de plagas y enfermedades que pueden dañar la producción. Alrededor del módulo debe mantenerse muy limpio, siempre con el objetivo de no permitir el acercamiento e ingreso de ningún patógeno [11]. Realizando todos los medios para evitar la contaminación del cultivo.

Para el control de colémbolos y de dípteros se recomiendan medidas preventivas como colocación de filtros junto a los ventiladores, eliminación de residuos, tratamiento térmico de los sustratos para eliminar huevos y larvas, etc.

5. Conclusiones

El endocarpio de coco puede ser usado como sustrato en el cultivo de pleurotus ostreatus, si se utiliza un tratamiento de desinfección de choque térmico y una reducción de partícula menor a 1 mm.

No se puede descartar el uso de endocarpio de coco su composición, ya que su bromatológica está constituida por carbohidratos estructurales que favorecen el desarrollo del hongo.

Los resultados concuerdan con otras investigaciones de P. ostreatus, que indican que el cultivo de orellanas puede ser rentable económicamente y aportaría en la mitigación de la problemática ambiental que generan los residuos agroindustriales.

El porcentaje de lignina, celulosa y hemicelulosa (compuestos Lignocelulósicos), presentes en el endocarpio usado en el cultivo de Orellana, presentan una relación de

celulosa 24.37%. < lignina 44.41%. Para un porcentaje alto en la lignina, se debe considerar una formulación para aumentar el contenido de lignina ya que esta determina la dureza de las maderas e interfiere con el desarrollo adecuado para la fijación y absorción de nutrientes, por esta razón es necesario realizar la reducción del tamaño de partícula.

La cantidad de nitrógeno presente en el endocarpio de Coco (0.29%), según la literatura consultada y los resultados obtenidos, es un determinante importante en el crecimiento del hongo.

Para el cultivo de pleurotus Ostreatus cultivado en sustrato de endocarpio de coco, se debe considerar una formulación con dos o más componentes, para obtener la cantidad de nutrientes necesarios en el crecimiento y fructificación del hongo.

Para evitar la contaminación del sustrato, el ambiente debe ser inocuo, y generar las condiciones ambientales adecuadas para el crecimiento del hongo, y evitar que otros hongos compitan con el Pleurotus Ostreatus, sin retardar el crecimiento o la invasión micelar, asegurando la mejor eficiencia biológica posible.

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Pulverizaciones agrícolas: Comparación de metodologías para su evaluación

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1 Introducción

Las enfermedades, plagas y malezas son cada vez más comunes y agresivas en los sisemas productivos, por lo que se requiere del uso de tecnologías de control apropiadas a cada situación. La eficiencia de las mismas influye en la cantidad de producto que llega al objetivo, mejorando la calidad de las aplicaciones y permitiendo la reducción en el uso de principios activos y contaminaciones indeseadas. La calidad de las aplicaciónes es evaluada por medio de colectores artificiales que a su vez son procesados con diversos programas informáticos [1];[2]. Estos colectores y programas pueden diferir en sus resultados. Se evaluó la calidad de aplicación con dos colectores artificiales diferentes, tarjetas Amarillas (papel hidrosensible Syngenta®) y tarjetas Blancas (papel fotográfico Glosy de 230 gr m^{-2}) y dos programas de procesamiento (CIR-1.5 y Gotas-PC). El ensayo se realizó en condiciones semicontroladas, sin viento y sin desuniformidades de la superficie del terreno. Se sutilizaron 2 pastillas diferentes, de igual caudal por minuto y separadas 0,52 m, trabajando a 2,5 bares (250 kpa) de presión y con una velocidad de trabajo del equipo de 17 km h^{-1} para erogar 50 l ha^{-1} (Ver Tabla 1).

Table 1. Pastillas características descripción

Pastillas	Ángulo	caudal	Tipo	Marca	Siglas
XR11002VP	110	02	Abanico	Teejet	AP
TXA8002VK	80	02	Cono Hueco	Teejet	CC

El botalón circuló a 0,75 m por encima de objetivos artificiales que poseian prismas cúbicos donde se colocaron los colectores en posición horizontal, arriba (Ar), adelante (AdH) y atrás (AtH) y en posicion vertical adelante (AdV) y atras (AtV). Los mismos se digitalizaron con scanner a 1200 dpi, para ser procesadas con los programas CIR-1.5 y Gotas-PC, obteniendo los siguientes parámetros:

- Densidad de impactos (N° de improntas cm^{-2}).
- Eficiencia (%), relación entre lo recogido en el objetivo y lo aplicado.

También se trabajó con trazador colorimétrico (Azul Brillante FD&CNº1) recolectado con papel de filtro el cual fue lavado con agua para cuantificar el trazador mediante espectrofotometría, y comparar con la eficiencia obtenida por los programas.

2 Resultados y discusión

El programa CIR es el más sensible en la detección de las gotas y distingue superposición de las mismas, presentando un mejor desempeño para la cuantificación de Impactos cm^{-2}. No se observaronn diferencias estadisticas entre tipos de colectores (Ver Fig.1).

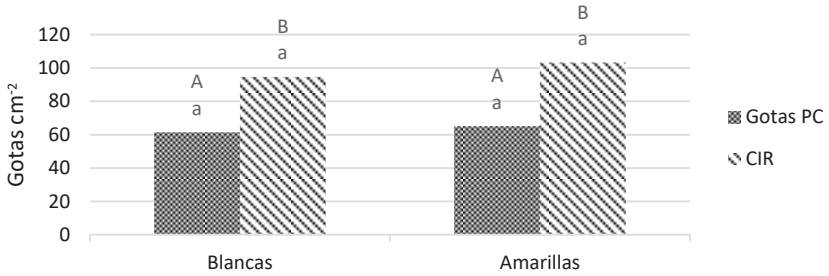

Fig. 1. Densidad de impactos por cm^{-2}. Comparación entre el cuantificado por los software CIR-1.5 y Gotas-PC utilizando los dos colectores, tarjetas blancas (papel Glosy) y tarjetas amarillas (papel hidrosensible). Letras mayúsculas diferentes significan diferencias estadísticamente significativas ($p \leq 0.05$) para el test de Ranks de Kruskal Wallis entre programas. Letras minúsculas diferentes significan diferencias estadísticamente significativas ($p \leq 0.05$) para el test de Ranks de Kruskal Wallis entre colectores

Los resultados demuestran que los colectores artificiales ubicados en las posiciones horizontales presentan mayor número de impactos que las verticales, ya que estas últimas son de mayor dificultad de alcance durante la pulverización, coincidiendo con [3–6]. Por otro lado, el programa CIR-1.5 contabiliza mayor número de gotas, con respecto al software Gotas-PC en todos los tratamientos realizados, sin importar el tipo de pastilla y tarjeta colectora, presentando las mismas tendencias de comportamiento en todas las posiciones; esto puede deberse a que Gotas-PC presenta dificultades para determinar superposiciones de impactos (propias de las gotas de mayor tamaño) y para reconocer gotas muy pequeñas lo que conlleva a un menor número de improntas cm^{-2} coincidiendo con [7] (Ver Fig.2 y Fig.3).

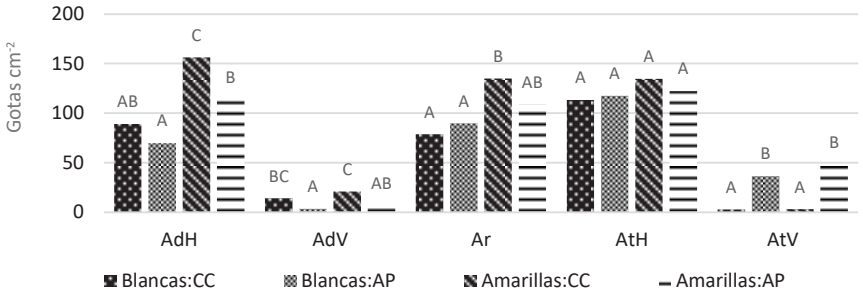

Fig. 2. Densidad de impactos cm^{-2} contabilizadas por el software Gotas-PC en las diferentes posiciones particionadas por colector tarjetas blancas (papel Glosy) y tarjetas amarillas (papel hidrosensible) y por pastilla AP y CC. Letras diferentes significan diferencias estadísticamente significativas ($p \leq 0.05$) para el test de Ranks de Kruskal Wallis dentro de cada posición.

Se pueden observar diferencias entre los colectores pero variables entre las posiciones y los programas. Esto probablemente se deba auna interaccion entre la capacidad de los programas de detectar diferentes tamaños de gotas y superposiciones de las mismas cuando alcanzan las distintas posiciones [7] [2]. Sumado a esto, los colectores de papel fotográfico disminuyen la expansión de las gotas generando diferentes tamaños de impronta que las tarjetas hidrosensibles, lo que colaboraría con estas diferencias tan variables [8].

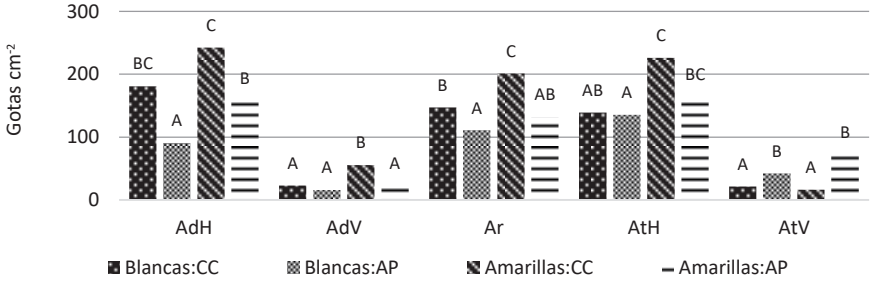

Fig. 3. Densidad de impactos cm^{-2} contabilizadas por el software CIR 1.5 en las diferentes posiciones particionadas por collector tarjetas blancas (papel Glosy) y tarjetas amarillas (papel hidrosensible) y por pastille AP y CC. Letras diferentes significan diferencias estadísticamente significativas ($p \leq 0.05$) para el test de Ranks de Kruskal Wallis dentro de cada posición.

Al estudiar la Eficiencia (%) a través de colectores fotográficos, tanto el software Gotas-PC como el CIR-1.5 arrojaron valores menores sin diferencias significativas con la metodología de trazador, demostrando un buen comportamiento por parte de los mismos. Mientras que, cuando se utilizaron colectores hidrosensibles, ambos software sobreestimaron la eficiencia de aplicación con relación al trazador. Esto puede deberse a que no todos los programas calculan el área de la gota de la misma forma, utilizando diferentes fórmulas de transformación de improntas en volumen [9], lo que seguramente genera errores entre programas. Los factores de corrección que utilizan los programas para calcular el volumen de la gota a partir de su impronta en el papel, están dados para trabajar con colectores hidrosensibles y no fotográficos (Ver Fig.4)

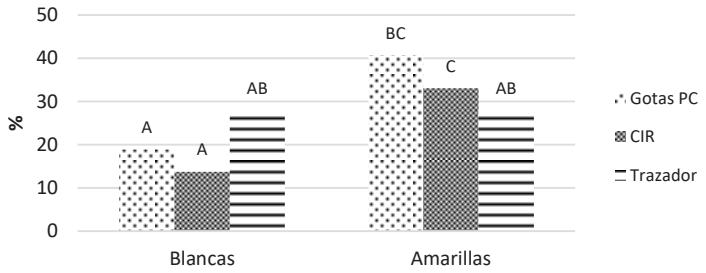

Fig. 4. Comparación de la eficiencia de aplicación cuantificada por los softwares CIR 1.5 y Gotas para pc con dos tipos de colectores, tarjetas blancas (papel Glosy) y tarjetas amarillas (papel hidrosensible) con respecto al trazador colorimétrico. Letras diferentes indican diferencias estadísticamente significativas ($p \leq 0.05$) para el test de Ranks de Kruskal Wallis.

Con el papel fotografico, el CIR 1.5 presenta diferencias con el trazador, aún siendo el del resultado más certero (sobreestima sólo un 18%). Gotas-PC no presenta diferencias significativas con el CIR 1.5 y el trazador, pudiendo deberse este comportamiento a la metodología estadística utilizada y a la gran variabilidad. Por otro lado, el programa Gotas-PC sobreestimó en un 45,9% la eficiencia cuando se emplearon colectores amarillos, probablemente por dificultades en transformar improntas en volumen. En este sentido, los propios fabricantes del software remarcan la necesidad de que la tarjeta hidrosensible presenten una baja densidad de impactos [10] [11].

Los diferentes colectores siguen la misma tendencia en todos los tratamientos, por consiguiente podrían utilizarse ambos para analizar la calidad de aplicación a campo, teniendo en cuenta que los porcentajes de eficiencia variarán según el colector utilizado.

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Keywords: Papel Glosy, papel Kromekote, CIR 1,5, Gotas PC.

Systematic Literature Review of Water-Energy Nexus: An Overview of the field and analysis of the top 50 influential papers

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Abstract— Water needs energy and energy needs water. In this context, the optimization of the use of each of these variables is a fundamental goal to tackle climate change and achieve sustainable development. The water-energy nexus has gained relevance in the literature through the study of their dependencies, with the objective of increasing their synergies and reducing their trade-offs. Moreover, the nexus approach has proven to be a useful methodology to evaluate the impact of a variable (or group of variables) in a specific system or network, as for example, the intricate network of the Sustainable Development Goals (SDG). The main purpose of this study is to improve the understanding of the water-energy nexus through a comprehensive literature review, based on the influence of the publications (citation-based approach). The methodology allows the identification of the top 50 most influential papers related to the water-energy nexus, based on the number of citations that it has, since its publication in a scientific journal. Additionally, it has been analyzed the main journals in this topic, the context and characteristics of the publications (geographical locations and study design), most cited authors, the timeline and evolution of the literature. Finally, the study seeks to improve the comprehension of the relevance of the dependencies and interactions between these variables, added to their fundamental roles in the whole system.

Keywords: Water-Energy Nexus, Nexus Approach, SDG, Sustainability.

1 Introducción

La era del antropoceno, con la actividad humana como principal responsable de la presión sobre los recursos naturales y el medioambiente. En ese sentido, en las últimas décadas, las estadísticas reflejan un rápido crecimiento del consumo y demanda mundial del agua y la energía.

Las proyecciones realizadas por agencias internacionales indican que el consumo de agua para generación de energía aumentará en 60% al 2040 [1]. De la misma manera, estudios independientes indican que el consumo mundial de agua fresca y energía podrían aumentar en 50% en el año 2050 (año base 2015) [2].

En este contexto, acompañados de situaciones climáticas más intensas (sequías más prolongadas, olas de calor, escasez de agua, etc.), la tendencia es un aumento de la presión sobre los recursos hídricos y los sistemas energéticos, los cuales ya pueden ser observados en algunas de las regiones más vulnerables. En algunos casos, estas situaciones pueden incluso propiciar tensiones geopolíticas, como los que se observan por ejemplo en la construcción de la Gran Represa del Renacimiento, sobre el río Nilo azul y que impacta directamente en el potencial consumo de agua de 3 países (Etiopía, Egipto y Sudán).

Adicionalmente, también existen preocupaciones por el impacto en el medioambiente, suponiendo el riesgo global de someter a una gran presión sobre estos 2 recursos fundamentales para la vida humana: el agua y la energía ([3] & [4]). Así, en ambos sentidos de la interacción agua-energía, se ha buscado optimizar la utilización del recurso, con el objetivo de aliviar la presión sobre los recursos agua y/o energía, reducir las emisiones de gases de efecto invernadero e impulsar el desarrollo sostenible ([1],[5],[6] & [7]).

Como lo menciona [1], el agua depende de la energía y la energía depende del agua. En lo que se refiere al estudio del impacto del agua sobre los sistemas energéticos, en análisis generalmente se orienta a la optimización del consumo de agua en la generación de energía, además de cuestiones de seguridad energética en contexto de políticas de racionamiento de consumo de agua ([8],[9],[10],[11],[12] & [13]). En sentido contrario, el estudio del impacto de la energía en los sistemas hídricos, se encuentra en la literatura que los mismos se orientan a mejorar la eficiencia energética de los sistemas de irrigación, sistemas de bombeo y extracción, sistemas de desalinización de agua, entre otras ([15],[16],[17],[18] &[19]).

El Foro Económico Mundial del 2008 es normalmente mencionado como el origen del concepto de análisis a través del nexo agua-energía, a pesar de que existen algunos estudios previos que ya mencionaban este enfoque ([4] & [14]). De la misma manera, es innegable, que el enfoque de nexos agua-energía también ha ganado tracción en la literatura a partir del año 2015, con la Agenda 2030 y sus Objetivos de Desarrollo Sostenible (ODS), los cuales identifican al agua (ODS6) y la energía (ODS7) como fundamentales para el desarrollo sostenible ([20],[21] & [22]). En este sentido existen muchos estudios analizando nexos entre los ODS, abarcando diversas combinaciones, como nexos agua-energía-alimentos, nexo agua-energía-cambio climático, entre muchas otras [20].

Esta investigación tiene como objetivo proveer una visión holística de la producción científica en el área del nexo agua-energía, comprender la evolución de la literatura en dentro de las ciencias, identificar tópicos y publicaciones de tendencia dentro de la misma área, mediante el análisis de diversos indicadores bibliométricos.

El artículo está organizado de la siguiente manera: primero, en la Sección II se detalla la caracterización del problema de investigación; en la Sección III se explica la metodología implementada para la revisión sistemática de la literatura del nexo agua-energía; en la Sección IV se procede a presentar los resultados obtenidos; y finalmente en la Sección V se presentan las conclusiones de la investigación.

2 Caracterización del problema

2.1 Interacciones y enfoque de nexos entre los ODS

El compromiso asumido por los países miembros de las Naciones Unidas en el año 2015, a través de la Agenda 2030 y sus Objetivos de Desarrollo Sostenible (ODS) para el período 2015-2030, ha sido un tema de gran interés en la producción científica ([23],[24] & [25]).

No obstante, a pesar del gran volumen de publicaciones en las diversas áreas de los ODS, aún existen brechas en la comprensión sobre el impacto (sinergias y trade-offs) de las interacciones de los ODS, aumentando en complejidad a medida que se avanza en el nivel de análisis (objetivos, metas e indicadores) ([26],[27],[28],[29],[30],[31],[32],[33],[34], [35],[36] & [37]).

En este sentido, el análisis de las interacciones a través del enfoque de nexos ha permitido evaluar simultáneamente las interacciones entre distintos sectores [20]. Así, la literatura de enfoque de nexos ha permitido evaluar el impacto de un grupo de ODS sobre otro objetivo particular o grupo de objetivos, de manera a identificar y/o comprender las relaciones de sinergia, trade-off o neutralidad entre los mismos. Algunos de los enfoques de nexos más estudiados incluyen: agua-energía-alimentos, agua-alimentos-clima, alimentos-energía, agua-energía, energía-crecimiento económico-clima, entre muchas otras ([20],[22],[38] & [39]).

En lo que se refiere al enfoque de nexos agua-energía, según [1] las interdependencias entre ambas tenderán a intensificarse rápidamente en el futuro. Los distintos escenarios de [1] subrayan la necesidad de optimizar el consumo y gestión del agua en los sistemas de generación de energía, de lo contrario podría incrementar las posibilidades de estrés hídrico en distintas regiones del mundo, en donde el consumo de energía está aumentando rápidamente. De la misma manera, la mejora en eficiencia energética y la optimización de los sistemas de irrigación, son temas ampliamente abordados por el enfoque de nexos agua-energía ([12], [15], [40], [41]).

3 Metodología

3.1 Criterios de selección de artículos

Esta etapa se ha realizado mediante búsqueda sucesivas, estructuradas y lógicas de palabras clave. Estas búsquedas se han orientado exclusivamente en artículos, a través de la identificación de palabras claves, las cuales en este caso particular han sido "nexo agua-energía", las cuales debían encontrarse presentes en el título del artículo.

En este sentido, la búsqueda ha sido realizada a través de la base de datos bibliográfica Scopus, la cual agrupa principalmente publicaciones de las revistas indexadas a la editorial Elsevier. Así también, la búsqueda ha sido realizada en idioma inglés (water-energy nexus), teniendo en cuenta que la mayoría de las publicaciones científicas, presentes en dicha base de datos bibliográfica, se encuentran publicadas en ese idioma.

Adicionalmente, se ha podido incorporar al análisis el trabajo de [1], el cual permite tener una visión más amplia de artículos, los cuales se encuentran publicados en otras bases de datos bibliográficas (Web of Science), distintas de Scopus.

En lo que se refiere a la búsqueda propia, se han realizado primeramente las búsquedas que se identifican en la Tabla 1.

Table 1. Palabras claves utilizadas en las búsquedas

1º Búsqueda	(TITLE-ABS-KEY("water-energy nexus" OR "WEN" OR "sustainable development" OR "sustainability" OR "Sustainable Development Goals" OR "SDG" OR "SDG7" OR "SDG6" OR "SDG synergy" OR "Water-Energy Development" OR "water-energy co-benefits" OR "nexus approach" OR "nexus development" OR "water for energy" OR "energy for water"))
2º Búsqueda	(TITLE-ABS-KEY("water-energy nexus" OR "SDG7" OR "SDG6" OR "water-energy co-benefits" OR "nexus approach" OR "water for energy" OR "energy for water"))
3º Búsqueda	(TITLE-ABS-KEY("water-energy nexus" OR "nexus approach" OR "water for energy" OR "energy for water"))
4º Búsqueda	TITLE ("water-energy nexus") AND DOCTYPE (ar)

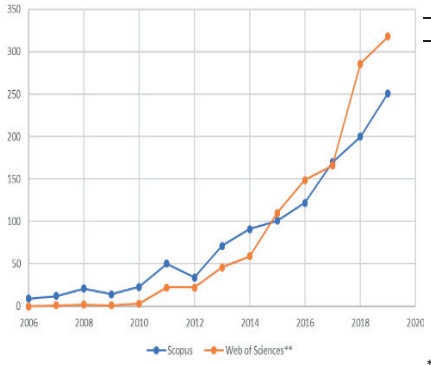
Como se observa en la Tabla 1, se ha realizado una búsqueda en 4 etapas, primeramente, se realizó la 1° búsqueda por palabras claves a partir del cual se obtuvieron 217.124 resultados. Teniendo en cuenta la gran cantidad de resultados, incluyéndose varias investigaciones no relevantes con el tema central de investigación, se ajustaron los parámetros de búsqueda en una 2° búsqueda, a partir del cual se obtuvieron 1.607 resultados. Luego, en la 3° búsqueda, considerando únicamente el enfoque de nexos, arrojó 1.169 resultados, aún así la cantidad de artículos no relevantes continuaba siendo elevada. Finalmente, se optó por ajustar los parámetros de búsqueda, orientándola exclusivamente a artículos con las palabras claves "water-energy nexus" en el título, con lo cual se pudo depurar la muestra y reducir la misma a 147 artículos (ver Material Complementario 1).

Se debe resaltar que, de acuerdo a los resultados de la búsqueda, la mayor parte de la literatura basada en el enfoque agua-energía ha sido principalmente publicada en la última década, siendo un tema relativamente reciente y que ha ganado mayor relevancia a través de su vinculación con los Objetivos de Desarrollo Sostenible (ODS6 y ODS7).

4 Resultados

4.1 Análisis de publicaciones

La distribución anual de publicaciones sobre el nexo agua-energía, como se ha mencionado previamente, ha crecido vertiginosamente a partir del año 2010. De hecho, el top 50 de los artículos más influyentes sobre este tema son prácticamente en su totalidad (a excepción de 1 artículo) del período 2011-2020 (ver Material Complementario 2).



Número de Publicaciones		
Año	Scopus	Web of Sciences**
2019	251	318
2018	200	286
2017	170	166
2016	122	149
2015	101	110
2014	91	59
2013	71	46
2012	34	22
2011	50	22
2010	23	3
2009	14	1
2008	21	2
2007	12	1
2006	9	-
Total	**1169**	**1185**

* Datos de Ding et al. (2020)

Fig. 1. Nº de publicaciones anuales en base al nexo agua-energía (3º filtrado)

Así también, vemos en la Fig. 1, que las publicaciones indexadas a las bases de datos de Web of Sciences (WoS) han crecido rápidamente, superando a las de la base de datos Scopus a partir del año 2015.

Los datos preliminares del año 2020 tienden a reforzar la tendencia, resaltando el creciente interés en este tópico en la literatura internacional.

4.2 Análisis de citaciones

En la presente sección se presenta el análisis de la revisión de la literatura en base a la evaluación del número de citaciones encontradas en la muestra de los artículos que han aplicado el enfoque de nexos agua-energía. Así también se identifica el top 50 de los artículos científicos más influyentes (de acuerdo al nº de citaciones) en este tópico, pudiendo observar la evolución del tema en la ciencia, sus ramificaciones en distintos sectores y disciplinas.

En la Tabla 2 se pueden observar los 10 artículos más citados, en base la metodología descrita previamente, aplicando el enfoque de nexos agua-energía.

Table 2. Lista de artículos con más citaciones (Top 10) *

Ranking	Título del Artículo	Autor/es	Nº Citaciones
1	The water-energy nexus in Middle East and North Africa	Siddiqi, A., Anadon, L.D.	295
2	Policy and institutional dimensions of the water-energy nexus	Scott, C.A., Pierce, S.A., Pasqualetti, M.J., (...), Montz, B.E., Hoover, J.H.	237
3	Linkage analysis for the water–energy nexus of city	Fang, D., Chen, B.	116
4	Optimal design and operations of supply chain networks for water management in shale gas production: MILFP model and algorithms for the water-energy nexus	Gao, J., You, F.	111
5	Water-energy nexus: A review of methods and tools for macro-assessment	Dai, J., Wu, S., Han, G., (...), Xue, W., Yang, Q.	97
6	Gaining perspective on the water-energy nexus at the community scale	Perrone, D., Murphy, J., Hornberger, G.M.	88
7	Evaluation of Spain's water-energy nexus	Hardy, L., Garrido, A., Juana, L.	84
8	Is there a water-energy nexus in electricity generation? Long-term scenarios for the western United States	Ackerman, F., Fisher, J.	83
9	Water-energy Nexus: A case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods	Pacetti, T., Lombardi, L., Federici, G.	69
10	Drought and the water-energy nexus in Texas	Scanlon, B.R., Duncan, I., Reedy, R.C.	63

*Citaciones en indexadas en base de datos bibliográficos de Scopus.

Es interesante destacar que, si bien se esperaría que los artículos más antiguos corran con ventaja por el tiempo que han estado disponibles para acumular citaciones, en la realidad se observa que esto no necesariamente se cumple. En el top 50 de los artículos más influyentes identificados previamente, la mayor cantidad de artículos corresponden al año 2018 (13 publicaciones), y el 80% de las publicaciones corresponden al período 2015-2019 (40 publicaciones), todo ello en correspondencia con la adopción de la

Agenda 2030 y los Objetivos de Desarrollo Sostenible a partir del año 2015 y su consecuente impacto en el análisis del enfoque de nexos para la medición del impacto e interacciones de los objetivos relativos al agua (ODS6) y energía (ODS7).

4.3 Revistas más influyentes relacionadas con el análisis del nexo agua-energía

En la Fig. 2 se pueden distinguir las revistas con mayor número de artículos publicados en referencia al nexo agua-energía, destacándose principalmente: Applied Energy y el Journal of Cleaner Production.

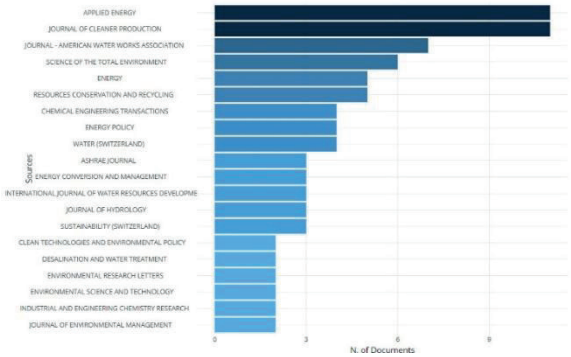


Fig. 2. Revistas con mayor nº de publicaciones (nexo agua-energía)

Luego, analizando únicamente el top 50 de publicaciones más influyentes, de acuerdo al número de citaciones, se observa que el 39% de las mismas se encuentran publicadas en 4 revistas: Applied Energy, Journal of Cleaner Production, Science of the Total Environment y Energy Policy.

No obstante, se debe resaltar que, de manera general, la distribución de publicaciones entre las distintas revistas científicas es bastante variada y diversificada, pudiéndose observar, en la muestra total de 147 publicaciones, un total de 80 revistas con publicaciones relacionadas al enfoque de nexos agua-energía.

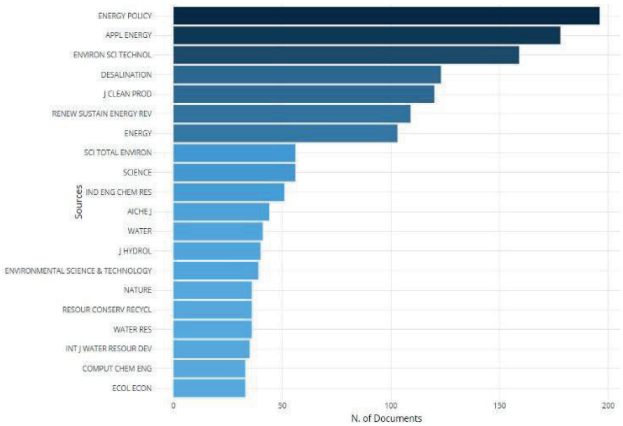


Fig. 3. Revistas con mayor nº de citaciones

Así también, se ha podido identificar en la Fig. 3, que no necesariamente revistas con mayor cantidad artículos publicados son los que acumulan más citaciones en la literatura del enfoque de nexos agua-energía (por ej. Energy Policy).

4.4 Autores más prolíficos

La literatura referente al nexo agua-energía es una literatura relativamente reciente, la cual ha ganado tracción principalmente en la última década (2010-2020). En ese sentido, como parte de los resultados obtenidos se observa que los autores más productivos en este tópico han acumulado entre 1 a 4 artículos publicados en diversas revistas científicas (Fig.4).

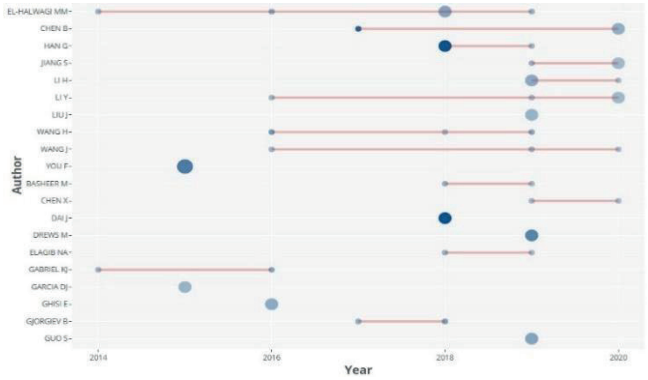


Fig. 4. Evolución de publicaciones de autores prolíficos

De la misma manera, se puede observar en la Fig. 5, que no existe una correlación relevante entre la cantidad de artículos publicados y la cantidad de citaciones acumuladas localmente por autor. La cantidad acumulada de citaciones locales de un autor indica su nivel actividad en una determinada área de estudio.

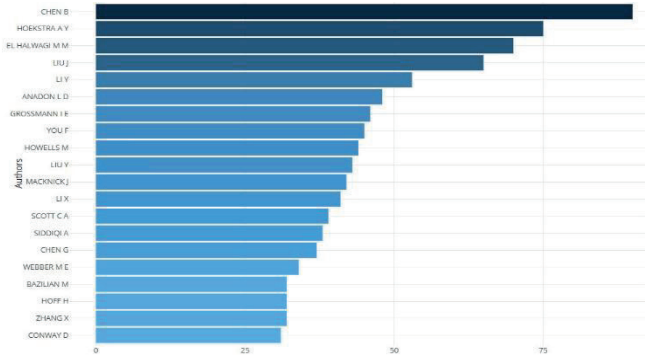


Fig. 5. Autores con mayor nº de citaciones locales

En lo que se refiere a la autoría principal de los trabajos publicados dentro del top 50 de los artículos más influyentes, no se observa ninguna brecha o predominancia de algún autor en particular. En este sentido, la mayoría de los autores principales en este grupo posee una única publicación, a excepción de 2 autores (K.J. Gabriel y B. Gjorgiev) quienes poseen 2 publicaciones cada uno, los cuales se enfocaron en la optimización del uso del agua en la industria y en la generación de energía.

En lo que se refiere al análisis geográfico de las publicaciones, en función a las afiliaciones de los autores, es importante destacar que el enfoque de nexos agua-energía es un tópico de tendencia principalmente en universidades y centros de investigación de China y EEUU, como se puede observar en la Fig. 6. En ese sentido, también se ha analizado en la muestra, la cantidad de veces que han sido citados los distintos países estudiados en los artículos publicados, observándose que EEUU acumula 806 citaciones, seguido por China con 169 citaciones y luego España con 143 citaciones

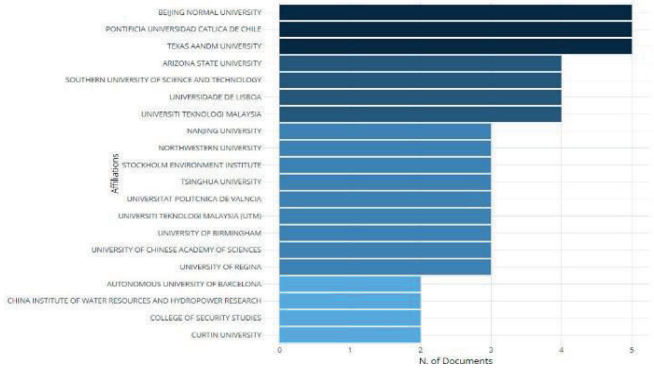


Fig. 6. Nº de publicaciones por afiliación

4.5 Análisis detallado de contenido del top 50 de artículos más influyentes

La literatura referente al enfoque de nexos agua-energía abarca una vasta diversidad de sectores y ciencias, lo que se refleja consecuentemente en los distintos tipos de publicaciones y objetivos perseguidos por cada uno de los mismos.

En este sentido, como resultado de la metodología implementada para la revisión bibliográfica, se puede distinguir que la mayor parte de los artículos en el top 50 en este tópico, se enfocan en el sentido de interacción agua → energía (43%), es decir, mejorar la comprensión del impacto del agua (i.e. escasez, políticas públicas, sistemas de bombeo, etc.) en la generación de energía.

No obstante, es importante resaltar que también existen otras alternativas al momento de realizar el análisis, como ser el sentido de interacción energía → agua, en donde el objetivo es cuantificar o comprender el impacto de la energía en el consumo de agua y/o en el servicio de tratamiento de aguas residuales. Así también, existen estudios más amplios, que realizan simultáneamente el análisis del nexo agua-energía en ambos sentidos de interacción. En la Tabla 3 se identifica el tipo de interacción analizada en cada uno de los artículos dentro del top 50 más influyentes seleccionados previamente.

Table 3. Top 50 artículos nexo agua-energía según tipo de interacción analizada

Agua → Energía	Energía → Agua	Agua←→Energía
[8] [9] [10] [11] [12] [13] [14] [44] [46] [47] [48] [49] [52] [53] [54] [57] [60] [66] [67] [71] [73] [75]	[15] [16] [17] [18] [19] [40] [41] [56] [58] [59] [61] [63] [65] [69] [70] [72]	[5] [6] [7] [42] [43] [45] [50] [51] [55] [62] [64] [68] [74]

Así también, se han analizados los resúmenes de los artículos seleccionados previamente, y a través del conteo de palabras claves, se han identificado tópicos de tendencia dentro de la misma área de estudio (enfoque de nexos agua-energía). Así, en la Fig. 7, se pueden distinguir todas aquellas palabras claves, identificadas en los resúmenes de los artículos, que han acumulado una frecuencia de 5 o más citaciones en el período de estudio.

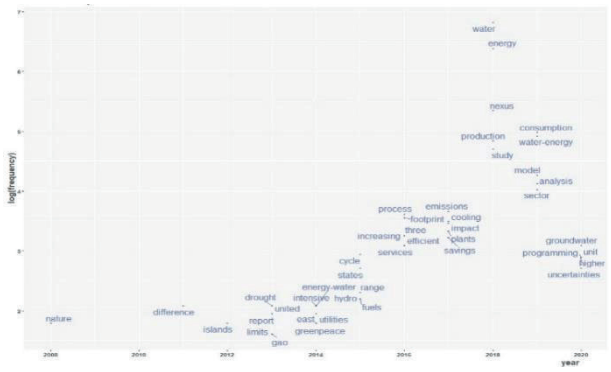


Fig. 7. Análisis de tópicos de tendencia (palabras claves)

Luego, se observa que algunas de las palabras claves, además de aquellas principales (agua, energía y nexo), incluyen: producción, consumo, estudio, modelización y análisis. De hecho, el consumo y la producción de agua y/o energía, son algunos de los elementos de estudio más recurrentes en el análisis del nexo agua-energía.

De la misma manera, se observa en la Fig. 8, que dentro de la intrincada red de coincidencias de la literatura de enfoque de nexos agua-energía, analizada a partir de los resúmenes de los artículos previamente seleccionados (n=147), que los nodos con mayor número de conexiones son: agua, agua-energía, nexo y energía. También, el algoritmo utilizado para la clusterización, distingue 3 grandes clústeres.

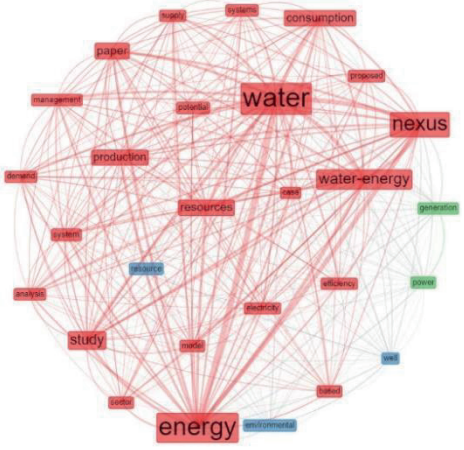


Fig. 8. Red de coincidencias en artículos de enfoque de nexos agua-energía

Así, se observa que variables que previamente ya habían sido identificadas como relevantes en el estudio del nexo agua-energía, efectivamente tienen un rol fundamental en la red de interacciones del tema analizado, como son: producción, consumo, recursos, demanda, electricidad, entre otras.

Como ya lo han identificado otros autores, la mayoría de los estudios con enfoque de nexos agua-energía son eminentemente cuantitativos, existiendo por el momento, una muy baja producción científica orientada a los aspectos de vinculación del análisis del nexo agua-energía para el diseño de políticas públicas y de administración eficiente de recursos naturales [1].

5 Conclusiones

La relación de dependencia, cada vez más intensa, entre el agua y la energía es innegable e inevitable, como lo han demostrado diversos autores. Esta relación entre 2 recursos fundamentales para la vida humana, y que han sido identificados como parte de los Objetivos de Desarrollo Sostenible (ODS6 y ODS7), tienen un impacto relevante en otros sistemas y sectores, como la producción de alimentos, cambio climático, emisiones de gases de efecto invernadero, crecimiento económico, entre otras.

Este trabajo ha realizado una revisión bibliográfica estructurada, mediante indicadores bibliométricos, de la literatura más influyente acerca del nexo agua-energía. En ese sentido, el principal aporte de la investigación ha sido la identificación de tendencias e influencias en la literatura del enfoque de nexos agua-energía, permitiendo una mejor comprensión de la evolución de la misma en la ciencia y su relevancia en distintos sectores y desde variadas perspectivas.

Los resultados demuestran un creciente interés en el nexo agua-energía, principalmente a partir del año 2010 en adelante, situación que ha reforzada a partir del año 2015 con la adopción de la Agenda 2030 de las Naciones Unidas. De la misma manera, se observa una gran representatividad de estudios orientados a la problemática en China y Estados Unidos, abarcando estudios a nivel urbano, local, regional, nacional o transnacional. Así también, se ha encontrado que los artículos identificados y relacionados al nexo agua-energía han sido publicados en una gran variedad (aproximadamente en 80 revistas) de revistas científicas, sin embargo, son 2 las que se destacan claramente sobre las demás: Applied Energy y el Journal of Cleaner Production.

Se observa una tendencia hacia un análisis del enfoque de nexos agua-energía orientados hacia la modelización y optimización del consumo y/o producción (generación) de estos recursos, teniendo en cuenta las proyecciones al alza de la demanda de ambos en el largo plazo, considerando los riesgos del cambio climático y la relevancia de la seguridad energética. Luego, alineados con estas tendencias, se observa en el mapa de relaciones que además de las palabras claves (agua, energía y nexos), existe un importante número de conexiones en la red entre otras variables ya identificadas previamente como: consumo, producción, electricidad y recursos.

Es importante tener en cuenta las limitaciones propias de la metodología implementada, considerando el limitado número de artículos analizados y su inscripción dentro de una única base de datos bibliográficos. No obstante, los resultados ofrecen un panorama global del enfoque de nexos agua-energía en la literatura y permiten establecer un marco conceptual más estructurado para futuras investigaciones orientadas a algunas de los tópicos de tendencia identificados en la investigación.

Finalmente, en relación a perspectivas futuras de investigación, se recomienda profundizar la comprensión del enfoque de nexos agua-energía, a nivel de metas y/o indicadores, de manera a identificar las sinergias y trade-off que aceleren el desarrollo sostenible de empresas, industrias, ciudades y/o países. Así también, existe un campo bastante fértil para la investigación del nexo agua-energía y su impacto en sistemas más amplios y dinámicos, como la generación de alimentos, crecimiento económico y/o cambio climático.

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Efecto del coadyuvante sobre la prestación de diferentes boquillas en espigas de Trigo

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Resumen. Las enfermedades fúngicas en el cultivo de trigo (Triticum aestivum) ocasionan pérdidas importantes en rendimiento y calidad de los granos. Los coadyuvantes deben considerarse como herramientas de manejo que mejoran el nivel de desempeño de los fitosanitarios. Se realizaron ensayos sobre espigas de un cultivo de trigo en antesis temprana (estado Z61) para evaluar el efecto de la adición de coadyuvante sobre la prestación de diferentes pastillas. El ensayo fue conducido en un esquema factorial de 4x2 con 10 repeticiones. Los factores fueron cuatro pastillas: abanico plano (XR11002), doble abanico asimétrico con aire inducido (AI3070), doble abanico simétrico con aire inducido (AI3030), cono hueco (TXA8002), y la adición de un codyuvante polifuncional. Se utilizaron tarjetas hidrosensibles y el programa CIR 1.5® para la determinación de densidad de impactos (imp cm^{-2}) y el Diámetro Volumétrico Mediano (µm), y mediante el uso del trazador Azul Brillante se determinó la deposición (%). Se realizó análisis de la varianza y las medias fueron comparadas por el test de Tukey ($p \leq 0,05$). La inclinación en 70º hacia atrás, mejora la cantidad de depósito sobre la espiga respecto a ángulos menores. La utilización de gotas finas y direcciones múltiples como las de la boquilla de cono hueco aumentan la deposición. El efecto del coadyuvante sobre las boquillas, no es concluyente y no se encontraron beneficios significativos en el uso de los mismos. La utilización de este tipo de coadyuvante provocó que la vena líquida se rompiera en un mayor número de impactos de menor diámetro.

Keywords: Palabras clave: Deposición, doble abanico; aire inducido.

1 Introducción

El trigo (Triticum aestivum) es el cereal de invierno más importante de la Argentina. Una de las principales problemáticas asociadas a este cultivo, es el manejo sanitario. La presencia de enfermedades foliares y de la espiga provocan grandes reducciones en el rendimiento y en la calidad de los granos. Para lograr disminuir el desarrollo de las mismas, se hace hincapié en la aplicación de fungicidas en el momento oportuno. En el caso de la fusariosis de la espiga(Fusarium graminearum), la aplicación debe ser en forma preventiva, con productos fungicidas que actúen principalmente como de contacto, por lo cual deben ser aplicados inmediatamente antes de la ocurrencia de la infección. [1] menciona que el momento óptimo para realizar el control es aproximadamente una semana después del inicio de la floración, máxima exposición de las anteras, pero generalmente las dificultades operativas para la aplicación condicionan

un tratamiento tardío. Este hecho pone de manifiesto que los resultados poco satisfactorios en el control químico a campo radican en la dificultad en alcanzar las anteras con la aspersión por la estructura de la espiga, en las técnicas de aplicación y en las condiciones ambientales al momento de la aplicación.

Experiencias usando fungicidas demuestran un amplio rango de eficiencia de acuerdo a múltiples factores tales como la elección del fungicida, el momento y método de aplicación, considerando los tipos de picos pulverizadores y las condiciones climáticas presentes durante el momento de aplicación como determinantes del éxito de la aplicación [2]. [3], establece que el éxito o fracaso de un tratamiento fitosanitario depende de cuatro factores básicos: buena calidad del agua, correcta elección de producto y dosis, momento oportuno de control y calidad de la aplicación. [4] citan que una buena aplicación implica una correcta distribución del fitosanitario, con mínimas pérdidas. Todas aquellas gotas que no lleguen al blanco, o que aun habiéndolo alcanzado no permanezcan retenidas sobre él, constituyen una pérdida de producto que reduce la eficiencia de la aplicación y se conoce genéricamente como deriva. La tecnología ha desarrollado dispositivos para disminuir las pérdidas por deriva, con la creación de nuevas boquillas, ya sean dotadas de pre-orificio o con inducción de aire, aumenta así el diámetro de gotas y disminuye la proporción de aquellas más propensas a la deriva. Sin embargo, existen opiniones encontradas en cuanto a la eficacia de las mismas. Al aumentar el tamaño de gota manteniendo constante el volumen de aplicación necesariamente se estará disminuyendo la cantidad de gotas formadas [5].

Para que la aplicación de agroquímicos sea adecuada, es necesario seleccionar el tamaño de gotas conforme a las condiciones climáticas imperantes durante el momento de la aplicación [6]. En este sentido, las gotas formadas por las boquillas de pulverización pueden tener su tamaño alterado por la presión de trabajo, formulación del producto utilizado, tipo y conformación de la boquilla. Estos últimos son los responsables de la calidad de la aplicación e interferirán sobre el caudal, cobertura del blanco y en la uniformidad de distribución del caldo.

La eficiencia de una pulverizadora puede estar afectada por la mala elección de las boquillas o estado avanzado de desgaste, mala ubicación en el botalón, altura inadecuada o por la presión de trabajo no aconsejada. Las boquillas son elementos básicos para una correcta uniformidad de distribución del producto sobre el cultivo y/o el suelo. Se debe elegir el tipo y modelo de boquilla de acuerdo al volumen que se va a pulverizar por hectárea, el producto, la plaga y el cultivo a tratar [7].

Al respecto, [8] sugiere para aplicaciones de fungicidas sistémicos una cobertura mínima de 30 a 40 gotas cm-2, mientras que, [9] establece un mínimo de 20 a 30 impactos cm-2 como norma general para productos sistémicos. [10] recomienda una densidad de al menos 50 a 70 impactos cm-2 para proporcionar resultados satisfactorios en la aplicación de fungicidas. En tanto que, [11] y [12] acuerdan que 60 impactos cm-2 son necesarios cuando se realizan tratamientos fúngicos para alcanzar eficacia biológica, dejando de lado los efectos de cobertura, características de la población de gotas, tamaño de gotas, amplitud relativa, uniformidad de distribución y recuperación de la solución aplicada sobre el objeto de aplicación. La amplitud relativa da una referencia de la homogeneidad de la clase de gotas que llegan al objetivo, cuanto más chico sea el número, más homogéneo es el espectro de gotas.

Sin embargo, además de la densidad de impactos, también es importante el diámetro de gotas para este tipo de productos. [13], recomiendan un diámetro de gotas (diámetro volumétrico mediano - DVM) entre 200 μm y 300 μm (gotas finas a medianas, según norma ASABE S572.1) como ideales para aplicaciones de fungicidas

sistémicos, relacionando el tamaño de la gota con la capacidad de deposición de las mismas, siendo que gotas finas (entre 106 µm y 235 µm, según ASABE S572.1) propician mayor cobertura pero presentan mayor riesgo de deriva. [14] encontraron menor diámetro de las gotas, mayor densidad y cobertura para las boquillas de cono hueco respecto a boquillas de abanico plano, bajo condiciones controladas. Sin embargo, estas últimas presentaron mayor uniformidad, atribuible, en principio, al perfil de distribución. Similares resultados presentaron [15], sobre un cultivo de soja (Glycine max (L) Merr) en R5, asociando la mejor distribución en el canopeo de las boquillas de cono hueco con la mayor cantidad de impactos de menor DVM, tanto en el estrato superior como en el inferior; las boquillas de doble abanico, en cambio, con un espectro de gotas de finas a medianas (entre 106 µm y 340 µm, según norma ASABE S572.1), no tuvieron mayor penetración después de los 0,20 m. Por su parte, [16] obtuvieron mejores porcentajes de cobertura, tanto en la espiga como en la hoja bandera de un cultivo de trigo, cuando pulverizaron con gotas finas (entre 106 µm y 235 µm, según norma ASABE S572.1).

Conforme a lo mencionado hasta aquí, la aplicación eficiente requiere una cobertura adecuada de la superficie objetivo con gotas de tamaño apropiado. La elección del patrón de gotas es muy difícil de definir, ya que depende de una serie de interacciones en la cual interviene el tipo de producto fitosanitario, su modo de acción, su formulación, la ubicación de la plaga, el tamaño de la plaga, las características de la superficie de la plaga y las condiciones ambientales [17]. Además de estar afectado por el diseño de la punta de pulverización, el patrón de gotas producido también sufre influencia de la presión de trabajo y de las características físicas del caldo que varían de acuerdo con la formulación del producto y el tipo de adyuvante que se utiliza. Debido a que la utilización de estos aditivos se ha incrementado notablemente en los últimos tiempos, es importante evaluar las características físicas que estas sustancias le confieren al caldo de pulverización y las posibles variaciones que pueden presentarse en el espectro de distribución. De hecho, el rendimiento de las boquillas pulverizadoras puede ser sustancialmente modificado a causa de los coadyuvantes, afectando tanto el proceso de formación de las gotas como el comportamiento de estas en contacto con el blanco, alterando el riesgo potencial de deriva de la aplicación [18].

Los coadyuvantes deben considerarse como herramientas de manejo que mejoran el nivel de desempeño de los fitosanitarios y la consistencia de los resultados. En este sentido, [19] encontraron una disminución de la capacidad antiderivante al evaluar la interacción de dos coadyuvantes comerciales, un tensioactivo y un antiderivante, utilizados conjuntamente durante el proceso de aplicación de agroquímicos. Por su parte, [20] evaluaron la influencia de diferentes adyuvantes multifuncionales asociados a cuatro formulaciones de glifosato en el control de Digitaria insularis L. La maleza mostró una alta sensibilidad a las diferentes formulaciones de glifosato, aunque la adición de los adyuvantes al caldo de pulverización, independientemente del tipo de sal, no tuvo beneficios significativos en el control de la misma, sin un aumento en la velocidad de acción del herbicida. [21] evaluaron el efecto de la adición de coadyuvantes (surfactantes) a los fungicidas en el control de enfermedades foliares y de la espiga en trigo. Los resultados demostraron que la adición de adyuvantes al caldo de pulverización interfirió positivamente en el desempeño de los fungicidas y afectó significativamente la severidad de enfermedades, el número de granos por espigas, la productividad y el retorno económico. De la misma manera, [22] estudiaron la combinación de adyuvantes y fungicidas sobre las características fisicoquímicas del caldo de pulverización y el control de enfermedades foliares en los cultivos de trigo y soja. Los mismos concluyeron que la adición de coadyuvantes al caldo de pulverización

redujo significativamente la tensión superficial de la mezcla respecto al fungicida sin aditivos, atribuyendo a esta característica la menor severidad e incidencia de enfermedades.

[23] evaluaron la interacción de dos boquillas, abanico plano inclinado y abanico plano con inducción de aire, con diferentes adyuvantes de uso agrícola en la estimación del riesgo potencial de deriva. Los resultados determinaron que la boquilla con aire inducido obtuvo el mayor DVM, menor porcentaje de gotas ≤ 100 µm, menor riesgo potencial de deriva y espectro de gotas más uniforme en comparación a la de abanico plano inclinado. La adición de adyuvantes, independientemente de sus propiedades, minimizó los riesgos potenciales de deriva en la boquilla de abanico plano inclinado en tanto que, en la de aire inducido, únicamente el polímero vegetal tuvo este efecto, siendo el más eficiente. [24] estudiaron la influencia de diferentes aditivos y boquillas en la deriva de glifosato. Los autores concluyeron que la reducción de la deriva de glifosato está relacionada con la selección correcta de la boquilla de pulverización. Las boquillas con aire inducido proporcionaron menor deriva que la boquilla de abanico plano convencional, así como menor densidad de impactos y mayor DVM en el objeto de aplicación. El comportamiento de los adyuvantes fue dispar, NP-10® y Emultec R® aumentaron la deriva mientras que Grap 'Oil®, Grap Super Gun®, Iharol® y Dash HC® disminuyeron la densidad de gotas derivadas cuando se utilizaron con la boquilla XR, en comparación con el testigo sin coadyuvantes. [25] evaluaron la incidencia de dos tensioactivos sobre el grado de cobertura, tanto en tarjetas hidrosensibles como en hojas de cultivo de soja, mediante el empleo una boquilla de abanico plano 80015 a 300 kPa de presión. El agregado de tensioactivos al caldo de pulverización incrementó el grado de cobertura, dado principalmente por un aumento en el DVM de los impactos que alcanzaron los objetivos. El nivel de cobertura logrado estuvo afectado por las características superficiales del blanco. [26] encontraron una tendencia al aumento en la densidad de impactos con el uso de tensioactivos. Los mismos mencionan que los adyuvantes con tensioactivos se usan con la finalidad de disminuir la tensión superficial e incrementar la adherencia por una mayor superficie de contacto, contrariamente a lo que ocurre cuando se utiliza agua como dispersante que produce efectos de alta tensión superficial lo que provoca que las gotas adopten la forma esférica, con poca superficie de contacto y con tendencia al escurrimiento. Del mismo modo, [27] indican que la reducción de la tensión superficial de las gotas aumenta las posibilidades de retención de las mismas, mientras que [23] encontraron que la adición de adyuvantes minimizó los riesgos potenciales de deriva en boquillas de abanico plano inclinado y abanico plano con inducción de aire. En tanto, [28] trabajaron con dos tipos de coadyuvante, aceite agrícola metilado y ésteres metílicos de ácidos grasos de aceites vegetales, para la aplicación de herbicidas en el control de malezas de hoja ancha. Encontraron que el uso de ésteres generó mayor cantidad de gotas finas a muy finas, probablementepor una mayor reducción de la tensión superficial del agua, con la consecuente pérdida de gotas en el ambiente de trabajo. A este efecto también le adjudicaron el "corrimiento" del DVM, observándose una diferencia entre la lectura del software y la clasificación de la tabla que aporta la marca de boquillas utilizadas.

[29] demostraron que las gotas gruesas (entre 341 µm y 403 µm, según norma ASABE S572.1) generadas por boquillas con aire inducido y la disposición de dos boquillas (una hacia adelante y otra hacia atrás), aumentan la deposición en objetivos verticales y horizontales de un cultivo de cereal. Los mismos aseguran que al aumentar el ángulo entre las dos boquillas, también aumentan los depósitos en dichos objetivos. También [30] sugieren, para un control eficiente de las enfermedades en

espiga, utilizar boquillas anguladas hacia atrás y una población de gotas medianas (entre 236 µm y 340 µm, según norma ASABE S572.1) o con aire inducido. Además, encontraron una tendencia hacia una mayor deposición sobre la cara trasera de las espigas respecto a la delantera, para todas las boquillas utilizadas. Sin embargo, el abanico con aire inducido y con una inclinación de 10° hacia atrás presentó la mayor deposición en ambas caras, mientras que el abanico convencional la menor. Por su parte, [31] recomiendan trabajar con boquillas de abanico plano orientadas en la dirección de avance, con una inclinación respecto a la horizontal de 30° hacia abajo y asistidas con una corriente de aire, asegurando una mayor deposición y cobertura sobre las caras de la espiga. En este sentido, [32] demostraron que los depósitos sobre espigas de trigo aumentaron a medida que la inclinación de la boquilla de abanico plano variaba de 10° a 40°.

En razón de lo expuesto, la pulverización es la forma de aplicación más común y difundida de fitoterápicos, pero sus resultados son variables y complejos, lo que hace importante su evaluación.

Teniendo en cuenta lo antes mencionado, el presente trabajo tiene por objetivos evaluar el efecto del agregado de coadyuvante en la prestación de distintas boquillas sobre el cultivo de trigo.

2 Materiales y métodos

Los ensayos tuvieron lugar en la Estación Experimental Julio Hirschhorn de la Facultad de Ciencias Agrarias y Forestales de la Universidad Nacional de La Plata (34° 59' S, 57° 59' W), situada en la localidad de Los Hornos de la ciudad de La Plata, Argentina. Las aplicaciones se efectuaron sobre un cultivo de trigo (Triticum aestivum) en la etapa de antesis temprana, estado Z61 según escala de Zadocks et al., (1974), correspondiente al período de cultivo de mayor susceptibilidad a la infección por Fusarium graminearum. Para realizar las aplicaciones, se utilizó un equipo pulverizador hidráulico montado con un tanque de 400 l de capacidad, ancho de labor de 8,4 m, portapicos múltiples distanciados a 0,525 m y altura de botalón respecto a la espiga de 0,35 m. La velocidad de desplazamiento del conjunto fue de 2,45 m s-1, la presión de trabajo de 300 kPa y la tasa de aplicación para todos los tratamientos de 103 l ha-1, en correlación con los volúmenes que se utilizan para tratamientos de fungicidas. Para las aplicaciones se utilizó agua y se agregó un trazador de tipo alimenticio, Azul Brillante (FD&C Azul No. 1) en una dilución de 13,073 g l-1. Con el objetivo de evaluar el efecto de la adición de un aditivo a la mezcla, se incorporó un coadyuvante polifuncional marca Rino® en una dosis de 30 ml hl-1. El mismo es un nonilfenol polietilenglicol éter que tiene las propiedades de ser adherente, dispersante, emulsionante, humectante y tensioactivo.

Las condiciones meteorológicas promedio durante el ensayo fueron de cielo descubierto, temperatura media de 29,4 ºC, humedad relativa del 42% y velocidad del viento de 4,5 km h-1 con ráfagas de hasta 11,3 km h-1.

Se utilizó un diseño factorial de 4x2 con diez repeticiones distribuidas completamente al azar. Se evaluaron cuatro diseños de boquillas, abanico plano 11002 (AP11002), cono hueco 8002 (TXA8002), doble abanico simétrico con inducción de aire 11002 (AI3030) y doble abanico asimétrico con inducción de aire 11002 (AI3070) que definieron los tratamientos. Cada uno de ellos fue evaluado con agua y con la mezcla de agua y coadyuvante, estableciéndose así dos subtratamientos para cada uno (Tabla 1).

Table 1. Boquillas utilizadas y condiciones operativas del conjunto tractor pulverizadora. P: presión de trabajo; q: caudal erogado por la pastilla; Va: velocidad de desplazamiento del conjunto; VA: volumen de aplicación; T: tratamiento; AP11002: boquilla de abanico plano 11002; TXA8002: boquilla de cono hueco; AI3030: boquilla doble abanico simétrico con inducción de aire; AI3070: boquilla doble abanico asimétrico con inducción de aire; St: Subtratamientos; Sc: sin el agregado de coadyuvante; Cc: con el agregado de coadyuvante

Boquillas	Presión (KPa)	q ($l\ min^{-1}$)	Va ($m\ s^{-1}$)	VA ($l\ ha^{-1}$)	Ángulo de pulverización	tipos de gotas (µm)*	T	St
Albuz AP11002®	300	0,8	2,45	103	110°	Fina	AP11002	Sc Cc
Teejet TXA 8002®	300	0,8	2,45	103	80°	Fina	TXA8002	Sc Cc
Hypro GAT 11002®	300	0,8	2,45	103	110° con inclinación en 30° hacia adelante 30° hacia atrás**	Media	AI3030	Sc Cc
Teejet AI3070 11002®	300	0,8	2,45	103	110° con inclinación en 30° hacia adelante 70° hacia atrás**	Media	AI3070	Sc Cc

*clases de gotas de las boquillas de acuerdo a ASABE S572.1 (ASABE, 2009)
**Inclinaciones con respecto al plano vertical central de la boquilla

Se estableció como objetivo de medición la espiga. La misma fue evaluada a través de dos metodologías. Por un lado, se determinó la deposición del caldo por medio de la cuantificación del trazador adicionado al mismo (Azul Brillante, FD&C Azul No. 1), conforme a la metodología propuesta por [33]. Para ello, luego de realizada la aplicación y del secado del pulverizado sobre el cultivo, se recolectaron diez espigas por repetición y se colocaron en recipientes individuales y herméticos. En el laboratorio, las muestras de material se lavaron con 30 ml de agua destilada y mediante un espectrofotómetro se realizó la lectura de fluorescencia del residuo recolectado. Con la medida de fluorescencia y a partir de curvas de calibración realizadas con concentraciones conocidas de trazador, se determinó la cantidad de pulverizado por espiga.

Por otro lado, se utilizaron tarjetas hidrosensibles Syngenta® de 3" x 1" a fin de caracterizar la población de gotas que alcanzó el objetivo. Para esto, mediante un tubo cilíndrico apoyado sobre la espiga, se colocaron cuatro tarjetas hidrosensibles simulando las caras de la misma: anterior, posterior, derecha e izquierda. Las tarjetas fueron digitalizadas con una resolución de 1200 dpi y procesadas por medio del programa CIR 1.5. Se realizó el conteo y cálculo de las variables repuesta sobre el promedio de cinco ventanas de medición. Las mismas fueron: Densidad de impactos (DI, imp. cm^{-2}) y Diámetro Volumétrico Mediano (DVM, µm).

Los datos obtenidos se analizaron mediante un ANOVA factorial y los promedios se compararon mediante la prueba de comparaciones múltiples de Tukey, con un nivel de significancia de α=0,05.

3 Resultados y discusión

3.1 Densidad de Impactos (DI)

En la Figura 1 se presenta el promedio de densidad de impactos sobre la espiga para cada tratamiento, con y sin el agregado de coadyuvante. En un análisis general de los valores, la boquilla TXA8002 tiene los mayores valores en tanto que, AI3030 y

AI3070 las menores densidades de impactos y AP11002 un comportamiento intermedio. No obstante esto, únicamente TXA8002 se diferencia significativamente de los demás tratamientos, mientras que AP11002 lo hace solamente de AI3070. La mayor densidad de impactos de la boquilla TXA8002 fue en parte informada por [14] y [16], quienes atribuyeron estos resultados al espectro de gotas de menor tamaño de las boquillas de cono hueco respecto a las demás. Relacionado a esto es que las gotas pequeñas tienen mayores probabilidades de depositarse que un mismo volumen representado por gotas más grandes, lo que explica el bajo rendimiento de AI3030 y AI3070. Estos resultados se corresponden con los de [24] quienes encontraron menor porcentaje de deriva y menor densidad de impactos con las boquillas con aire inducido respecto a la boquilla de abanico plano convencional.

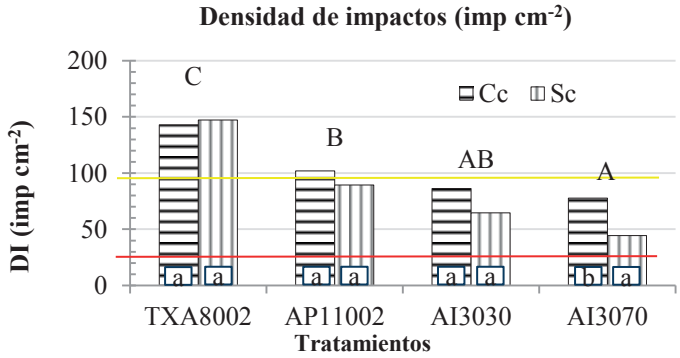

Fig. 1. Densidad de impactos sobre la espiga para cada tratamiento y subtratamiento. AP11002: abanico plano 11002; TXA8002: cono hueco 8002; AI3030: doble abanico simétrico con aire inducido 11002; AI3070: doble abanico asimétrico con aire inducido 11002; Cc: con el agregado del coadyuvante; Sc: sin el agregado del coadyuvante. Letras minúsculas diferentes en las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre subtratamientos para cada boquilla. Letras mayúsculas diferentes sobre las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre tratamientos

Los resultados corroboran las dificultades de las gotas para alcanzar el objetivo vertical, vinculadas a la propia estructura de la espiga y su orientación, siendo relativamente más fácil que las mismas alcancen las partes orientadas horizontalmente, como la hoja bandera. El bajo desempeño de las boquillas AI3030 y AI3070 no condice con las recomendaciones de [30] respecto a la utilización de boquillas anguladas hacia atrás y una población de gotas medianas o inducidas con aire para un control eficiente de las enfermedades en espiga. No obstante esto, todas las boquillas alcanzaron el mínimo de 20 a 30 impactos cm^{-2} que establece [9] para productos sistémicos, como así también las 30 a 40 gotas cm^{-2} recomendadas por [8] para alcanzar eficiencia biológica en tratamientos fúngicos con productos sistémicos. Sin embargo, en este tipo de cultivo, la estructura y fisiología de la espiga hacen que los productos fungicidas actúen principalmente como de contacto y no sistémicos [1], requiriendo para su control un mínimo de 60 impactos cm^{-2} recomendados por [11] y [12] y hasta 70 impactos cm^{-2} de acuerdo a [10]. La boquilla AI3070 es la que registra los menores valores, por lo que en este parámetro no alcanza una mayor aptitud con respecto a las demás. En este sentido, esta alternativa sería la más complicada en alcanzar el número de impactos requerido ya que la densidad de impactos promedio sobre la espiga fue de 61 gotas cm^{-2}, en tanto que las demás opciones (AI3030, AP11002 y TXA8002) lo superan, sin comprometer la aplicación. Sin embargo, AI3030 con 76 impactos cm^{-2}

sobre la espiga, apenas logran los requerimientos anteriormente mencionados, siendo probable que se ponga en riesgo la eficacia de la aplicación si las condiciones ambientales empeoran.

En cuanto al efecto de la adición del coadyuvante Rino® sobre la variable densidad de impactos, únicamente el tratamiento AI3070 presentó significativamente mayor número de impactos con el agregado del aditivo al caldo de pulverización. No obstante esto, se manifiesta en los tratamientos una tendencia hacia una mayor densidad de impactos con la adición del coadyuvante salvo para la boquilla TXA8002. La mayor DI, por la incorporación del coadyuvante, puede deberse a la menor tensión superficial de las gotas lo que permite que las mismas se aplanen más y reboten menos y se adhieran más al objetivo, aumentando la densidad de impactos en el mismo. En coincidencia con esto, [26] encontraron una tendencia al aumento de la DI con el uso de adyuvantes. Los mismos mencionan que los adyuvantes con tensioactivos se usan con la finalidad de disminuir la tensión superficial e incrementar la adherencia por una mayor superficie de contacto, contrariamente a lo que ocurre cuando se utiliza agua como dispersante que produce efectos de alta tensión superficial lo que provoca que las gotas adopten la forma esférica, con poca superficie de contacto y con tendencia al escurrimiento. Del mismo modo, [27] indican que la reducción de la tensión superficial de las gotas aumenta las posibilidades de retención de las mismas, mientras que [23] encontraron que la adición de adyuvantes minimizó los riesgos potenciales de deriva en boquillas de abanico plano inclinado y abanico plano con inducción de aire.

Si bien las diferencias son insignificantes, el menor número de impactos de la boquilla de cono hueco ante la incorporación del aditivo pudo deberse a la conjunción de gotas de tamaño fino y condiciones ambientales de 29,4 ºC y 42% de HR registradas al momento de la aplicación. Estas variables pudieron predisponer a una mayor termoderiva de las gotas y consecuentemente un menor número de impactos en los objetivos cuando se utilizó el coadyuvante. La disminución de la tensión superficial del líquido por el agregado del coadyuvante pudo ocasionar un rompimiento de la vena líquida en un mayor número de gotas de menor tamaño, resultando en un diámetro de gota menor al mencionado por el fabricante y susceptible de ser derivado. Estos factores podrían reducir la mejora producto del efecto de una mayor retención de las gotas en el objetivo por una menor tensión superficial. No obstante la explicación dada anteriormente, el comportamiento de XRA8002 coincide con lo mencionado por [19] quienes encontraron que el uso de tensioactivo puro incrementó significativamente la cantidad de líquido derivado.

3.2 Diámetro Volumétrico mediano (DVM)

El Diámetro Volumétrico Mediano (DVM o DV0.5) es el diámetro de la gota que separa la población de gotas ordenadas de menor a mayor en dos mitades de igual volumen de líquido [6]. En la Figura 2 se grafican los valores promedio de esta variable sobre la espiga para cada tratamiento y subtratamiento. En un análisis general, TXA8002 presentó significativamente los menores DVM, mientras que AI3070 tuvo significativamente los mayores diámetros y AP11002 y AI3030 un comportamiento intermedio sin diferenciarse estadísticamente entre sí.

Los resultados, fueron consecuentes con los tamaños de gotas que caracterizan a las boquillas, TXA8002 y AP11002 tuvieron los menores diámetros, mientras que AI3030 y AI3070 los mayores valores. Estas diferencias fueron en parte informadas por [23] y [24] quienes además hicieron hincapié en los menores riesgos potenciales

de deriva de las boquillas con aire inducido respecto a las convencionales. Los menores DVM de la boquilla de cono hueco respecto al abanico plano convencional, coinciden con lo informado por [14] y [15] al evaluar similares boquillas bajo condiciones controladas y sobre un cultivo de soja respectivamente. Sin embargo, los menores diámetros de TXA8002, 150 µm aproximadamente en promedio, no entran dentro de las recomendaciones de [13] para aplicaciones de fungicidas sistémicos, ya que las mismas propician mayor riesgo de deriva. Los mismos autores sugieren gotas entre 200 µm y 300 µm como ideales para este tipo de aplicaciones, siendo el abanico plano convencional y AI3030 las que mejor se ajustan a estos diámetros, con un DVM de 205 µm y 214 µm, respectivamente. La boquilla de doble abanico asimétrico alcanzó valores de DVM de 330 µm, lo que supone que las gotas difícilmente puedan atravesar el canopeo y por lo tanto queden retenidas en los estratos superiores. Similares resultados fueron obtenidos por [15] sobre un cultivo de soja en R5 donde las boquillas de doble abanico con un espectro de gotas de finas a medianas no tuvieron mayor penetración de los 0,20 m.

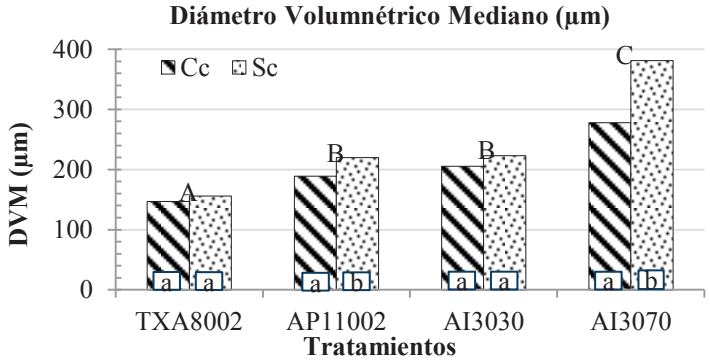

Fig. 2. Diámetro Volumétrico Mediano (DVM) sobre la espiga para cada tratamiento y subtratamiento. AP11002: abanico plano 11002; TXA8002: cono hueco 8002; AI3030: doble abanico simétrico con aire inducido 11002; AI3070: doble abanico asimétrico con aire inducido 11002; Cc: con el agregado del coadyuvante; Sc: sin el agregado del coadyuvante. Letras minúsculas diferentes en las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre subtratamientos para cada boquilla. Letras mayúsculas diferentes sobre las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre tratamientos

Un análisis diferente se puede realizar cuando se comparan los DVM de las poblaciones de gotas que alcanzaron el objetivo con el informado por los fabricantes para cada boquilla, de acuerdo a la presión de trabajo y caudal de las mismas. En este sentido, TXA8002, AP11002 y AI3030 presentan como DVM de referencia valores de 193 µ, 219 µ y 333 µ (Dowling, 2017*) respectivamente, mientras que las poblaciones de gotas que alcanzaron las espigas presentaron valores de DVM menores a los citados. Estos resultados reafirman que las gotas de menor tamaño, independientemente del DVM de la boquilla, alcanzan una menor velocidad final de caída y quedan suspendidas por más tiempo en el aire lo que las deja expuestas a condiciones de evaporación y a ser arrastradas por el viento y depositarse en la espiga. En cambio, las gotas de mayor tamaño por su peso y velocidad de caída, tienden a quedar retenidas en superficies horizontales de los estratos superiores, como sucede con la hoja bandera en el cultivo de trigo.

Al analizar los DV0.1 de referencia (diámetro de gota por debajo del cual se encuentra el 10% del volumen total del líquido pulverizado), los mismos tienen la misma tendencia que se observó para los DVM, la boquilla TXA8002 con 97 µ es la de menor DV0.1, seguido por AP11002 con 108 µ y AI3030 con 166 µ (Dowling, 2017[1]). Si bien las diferencias entre diseños de boquillas son chicas, principalmente entre las convencionales, los valores demuestran la gran proporción de gotas finas que se generan cuando se trabaja con pulverizaciones hidráulicas, independientemente del diseño de boquilla utilizado.

De acuerdo a la ficha de datos de AI3070, la misma posee un DV0.5 de 270 µ, valor menor al que se encontró en la espiga. Esto estaría indicando que la población de gotas que alcanzó el objetivo es más gruesa que la población de gotas que salió de la boquilla, lo que puede deberse a las condiciones atmosféricas de temperatura y humedad relativa, que pudieron disminuir por evaporación el tamaño de las gotas, afectando en mayor medida a las más chicas. Además, se puede adjudicar estos mayores DV0.5 a una inexactitud de la metodología , siendo que algunas gotas visualizadas en el papel podrían ser el resultado del solapamiento de varias gotas, por lo que el diámetro de las gotas tomado por el programa sería la combinación del diámetro de varias gotas pequeñas y no de una grande.

Estos resultados concuerdan con lo señalado por [28] quienes en la evaluación de diferentes boquillas hallaron discrepancia en el tamaño de las gotas (DVM) entre la lectura del software y la clasificación de la tabla que aporta la marca de las boquillas utilizadas.

En el análisis del efecto de la adición del coadyuvante al caldo de aplicación sobre la variable Diámetro Volumétrico Mediano, los resultados no fueron los esperados. Todos los tratamientos obtuvieron un DVM menor cuando se incorporó el aditivo a la mezcla, siendo las diferencias significativas en los tratamientos AP11002 y AI3070. De acuerdo a las propiedades del aditivo utilizado (adherente, dispersante, emulsionante, humectante y tensioactivo) se hubiese esperado un aumento del DVM por una disminución de la tensión superficial de las gotas. En acuerdo con esto, [25] obtuvieron un incremento del grado de cobertura, dado principalmente por un aumento en el DVM con el agregado de tensioactivo al caldo. La menor tensión superficial del caldo de aplicación provoca que las gotas cuando impactan en el objetivo de aplicación se expanden y disminuya el ángulo de contacto con la superficie, aumentando así su mojabilidad. Estas características se traducen en una mayor impronta de las gotas sobre las tarjetas hidrosensibles y consecuentemente un mayor diámetro. Contrariamente, las boquillas presentaron un menor diámetro volumétrico mediano con el coadyuvante, lo que implica una población de gotas de menor tamaño y consecuentemente mayores riesgos de deriva. Existen antecedentes que avalan una disminución en el DVM por la incorporación de un tensioactivo al caldo de aplicación. En este sentido, [18] obtuvieron una disminución del DVM cuando utilizaron un surfactante como coadyuvante respecto al agua como testigo. Estos resultados permiten acordar con la hipótesis ad hoc de [28] quienes adjudican al uso de ésteres metílicos de ácidos grasos de aceites vegetales la capacidad de una mayor reducción de la tensión superficial del agua, con la consecuente pérdida de gotas en el ambiente de trabajo por una mayor producción de gotas finas y muy finas, lo que traería aparejado un corrimiento del DVM. En este sentido, y en coincidencia con los resultados, [19] encontraron un incremento significativo de líquido derivado cuando utilizaron tensioactivo puro en relación con el agua. Del mismo modo, [17] menciona que la dis-

[1] Dowling, L. 2017. Pesticide Application Technology Laboratory de la Universidad de Nebraska para Pentair. Comunicación Personal

minución de la tensión superficial del caldo produce una disminución en el tamaño de las gotas y un aumento en el ángulo de aspersión.

De acuerdo a los resultados, los efectos del aditivo pueden ser contrapuestos. Por un lado, la utilización de este tipo de coadyuvante en la mezcla provocó que la vena líquida se rompiera en un mayor número de impactos de menor diámetro que si las condiciones ambientales son favorables, el DVM de la población de gotas que alcanza el objetivo disminuye. Si las condiciones ambientales favorecen a una evaporación y exoderiva, las gotas de menor tamaño no alcanzan el objetivo y consecuentemente el DVM de esa población aumenta.

Conforme a lo analizado hasta aquí, los resultados no fueron lo suficientemente decisivos como para concluir respecto al efecto del coadyuvante. Esto podría deberse a la complejidad del proceso de aplicación donde confluyen distintos factores como tamaño de boquilla, presión de trabajo, velocidad de avance, altura de botalón, características del caldo, condiciones ambientales al momento de la aplicación y características de la superficie objetivo que interactúan de manera diferente según el diseño de la boquilla, afectando directa e indirectamente a la población de gotas. En este sentido, [17] menciona que los coadyuvantes pueden generar interacciones entre la densidad, viscosidad y tensión superficial y pueden afectar de manera diferente a una boquilla de abanico plano que a una del tipo cono hueco.

3.3 Deposición (%)

En lo referente a la recuperación del producto sobre la espiga, independientemente de la incorporación o no del coadyuvante al caldo (Figura 3), la boquilla TXA8002 registró los mayores valores, cercanos al 55%, diferenciándose significativamente de los demás tratamientos, en tanto que AP11002 y AI3030 presentaron los menores porcentajes, cercanos al 30%, pero sin diferenciarse entre sí. En tanto, AI3070 con un porcentaje de depósito de 41,5% tuvo un comportamiento intermedio, significativamente diferente a las demás boquillas. Estos resultados ponen en discusión las dificultades para las recomendaciones de la dosis de producto, dadas las diferencias de deposición que se alcanzan. No existe una tendencia clara y los resultados no permiten asociarlos a una única variables que pueda explicar los diferentes comportamientos. Esto implicaría que el tamaño reducido de las de la población de gotas de la boquilla de cono hueco convencional favoreció en mayor medida la retención del caldo sobre la estructura vertical. La proyección angulada de AI3070 mejoró significativamente la deposición sobre la espiga con respecto a los demás abanicos planos, pero fue significativamente inferior a TXA8002. Estos resultados parecen indicar que a pesar de la intrincada e irregular superficie de la espiga, no se alcanza una adecuada captación y retención de la solución asperjada cuando aumenta el DVM de la población de la población de gotas.

Los resultados concuerdan con lo mencionado por con [13] quienes asocian la deposición con el tamaño de gotas, siendo que gotas finas resultan en mejor cobertura y penetración. Sin embargo, difieren en parte con lo mencionado por [29] quienes demostraron que las gotas gruesas aumentan la deposición en objetivos verticales y horizontales, corroborándose con el mayor DVM de AI3070. Estos últimos autores también aseguran que, al aumentar el ángulo entre las boquillas dobles, aumentan los depósitos en los objetivos, lo que fue ratificado en este trabajo por los mayores porcentajes de deposición de AI3070 respecto a AI3030. Esto mismo fue informado por [31] adjudicando a la angulación de 60º hacia adelante (inclinación respecto a la horizontal de 30º hacia abajo) una mayor deposición y cobertura sobre las caras de la

espiga. Del mismo modo, [29] mejoraron significativamente la deposición total sobre objetivos verticales cuando utilizaron la boquilla AI3070 11003 respecto a AIXR 11003 y AITTJ60 11003, adjudicando principalmente este comportamiento a un incremento del depósito en la cara posterior del objetivo.

En el análisis comparativo de las boquillas doble abanico respecto al abanico convencional, AI3070 alcanzó un 37% más de deposición respecto a AP11002 en tanto que AI3030 produjo un 7% menos de deposición. En parte estos valores acuerdan con [32] respecto a un incremento en la deposición a medida que la inclinación de la boquilla aumenta de 10º a 40º. Sin embargo, y de acuerdo a los resultados del ensayo, la inclinación en 30º de la alternativa AI3030 no fue suficiente para mejorar los depósitos, siendo necesaria una mayor angulación para incrementar los mismos. Del mismo modo, [5] encontraron un 73% más de deposición sobre la espiga cuando trabajaron con boquillas doble abanico TJ608002 en comparación con un abanico plano, atribuyendo esta mejoría al doble perfil de pulverizado.

De los resultados obtenidos se desprende que el diseño de la boquilla afecta significativamente los volúmenes recogidos en el objetivo, en coincidencia con [29] La combinación de una pulverización dirigida hacia el objetivo junto con un tamaño de gota reducido, pareciera ser la mejor alternativa para lograr una mayor tasa de recuperación sobre objetivos verticales, en condiciones atmosféricas compatibles con dicho tamaño, escasa velocidad de viento, temperaturas no demasiado altas y alta humedad relativa.

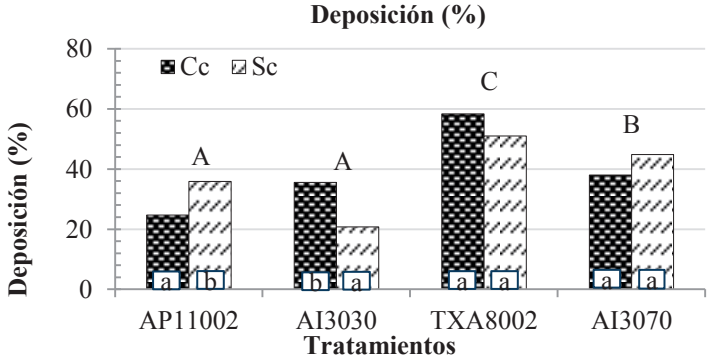

Fig. 3. Deposición (%) sobre la espiga para cada tratamiento y subtratamiento. AP11002: abanico plano 11002; TXA8002: cono hueco 8002; AI3030: doble abanico simétrico con aire inducido 11002; AI3070: doble abanico asimétrico con aire inducido 11002; Cc: con el agregado del coadyuvante; Sc: sin el agregado del coadyuvante. Letras minúsculas diferentes en las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre subtratamientos para cada boquilla. Letras mayúsculas diferentes sobre las columnas indican diferencias significativas ($p \leq 0,05$) según el test de LSD Fisher entre tratamientos

Las metodologías de evaluación utilizadas presentan ventajas y desventajas que resultan complementarias al momento de realizar un análisis completo de los parámetros de caracterización de la aplicación. Por un lado, el análisis digital de las tarjetas hidrosensibles permite de manera rápida y sencilla caracterizar el espectro de gotas con el que se está aplicando. Por otro lado, la utilización de trazadores posibilita realizar estudios de deposición en objetivos naturales, siendo una técnica de fácil manipulación, confiable y económica, en acuerdo con [33].

En lo que respecta al efecto del coadyuvante sobre el porcentaje de líquido recogido, únicamente se observaron diferencias significativas sobre la espiga con las boqui-

llas AP11002 y AI3030, aunque el resultado no fue el mismo para los dos tratamientos. Con la boquilla AI3030 se logró significativamente mayor deposición cuando se agregó el coadyuvante al caldo, mientras que con AP11002 se observó lo opuesto.

El comportamiento diferencial de los tratamientos ante la adición del coadyuvante, permite agrupar a las boquillas en dos grupos. Por un lado, los picos de tipo abanico convencional y doble abanico asimétrico que tuvieron una respuesta negativa a la incorporación del coadyuvante al caldo y, por otro lado, el cono hueco convencional y el doble abanico simétrico que se mostraron favorecidos por el agregado del coadyuvante. Estos resultados exponen nuevamente que el efecto del coadyuvante sobre las boquillas no es concluyente y coincide con lo observado por [20] quienes no encontraron beneficios significativos en el uso de aditivos, luego de evaluar diferentes coadyuvantes multifuncionales. Contrario a estos resultados, [21] demostraron que la adición de adyuvantes al caldo de pulverización interfirió positivamente en el desempeño de los fungicidas. Del mismo modo, [22] concluyeron que la adición de coadyuvantes al caldo redujo significativamente la tensión superficial de la mezcla, atribuyendo a esta característica la menor severidad e incidencia de enfermedades. Si bien en el ensayo no se evaluó la acción de un fungicida y su interacción con el coadyuvante, lo observado hasta aquí indicaría que no hubo modificaciones contundentes en la aplicación que permitan adjudicarle al aditivo un efecto positivo sobre las características del caldo.

4 Conclusiones

De los resultados, se desprende la importancia de la selección de las boquillas acorde al objetivo de aplicación y a las condiciones climáticas al momento de la misma. La inclinación en 70º hacia atrás, mejora la cantidad de depósito sobre la espiga respecto a ángulos menores. La utilización de gotas finas y direcciones múltiples como las de la boquilla de cono hueco aumentan la deposición en el objetivo vertical. Respecto al efecto del coadyuvante sobre las boquillas, no es concluyente y no se encontraron beneficios significativos en el uso de los mismos. La utilización de este tipo de coadyuvante en la mezcla provocó que la vena líquida se rompiera en un mayor número de impactos de menor diámetro que si las condiciones ambientales son favorables, el DVM de la población de gotas que alcanza el objetivo disminuye. Si las condiciones ambientales favorecen a una evaporación y exoderiva, las gotas de menor tamaño no alcanzan el objetivo y consecuentemente el DVM de esa población aumenta.

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Eficiencia espacial en la atención primaria de la salud en *Bahía Blanca*

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Abstract. Dos de las decisiones más importantes en la gestión de los servicios de salud son el número y la ubicación de las instalaciones que se crearán. Ambas decisiones tendrán una influencia decisiva en los gastos del sistema de salud y en el uso efectivo de dichos servicios por parte de sus beneficiarios. El objetivo de este trabajo consiste en evaluar la eficiencia espacial de la red de centros de atención primaria de la salud (CAPS) de la ciudad de Bahía Blanca (Argentina). Para ello, se comparan las distancias que los usuarios deben recorrer para asistir a un CAPS en la actualidad, con las distancias que deberían recorrer si su localización fuera óptima. La localización óptima se determinó utilizando un modelo P-media con restricciones de capacidad. La demanda anual de consultas médicas de cada nodo de demanda se estimó multiplicando el número de habitantes de dicho nodo por un índice socioeconómico. Los resultados obtenidos ponen en duda la eficiencia espacial de la red de CAPS de la ciudad de Bahía Blanca. En todos los escenarios estudiados, solo el 11% de los CAPS actualmente abiertos se colocan en sus ubicaciones óptimas. Una reorganización de la red de atención (manteniendo la misma capacidad y cantidad de CAPS abiertos que en la situación actual) podría disminuir las distancias de viaje (tanto del sistema total como el promedio por consulta) en un 36%. Además, la distancia recorrida por los usuarios que viven más lejos del CAPS abierto más cercano podría reducirse a casi la mitad.

Keywords: Primary health care centers; Spatial Efficiency; Optimal location; Bahía Blanca (Buenos Aires, Argentina)

1 Introducción

La gestión de los servicios de salud públicos es una de las mayores preocupaciones de los estados modernos, debido en parte a la gran cantidad de recursos monetarios que implica el cuidado de la salud. Una de las decisiones más importantes relativas a la provisión de servicios médicos sanitarios es la referida a la localización de los centros de salud, ya que tanto la cantidad de instalaciones a establecer como su ubicación influyen en los costos del sistema y en la utilización efectiva de los servicios por parte de los usuarios [1]. Asimismo, es necesario tener en cuenta que toda la población debería tener un fácil acceso a los servicios de atención primaria de la salud, y que un acceso deficiente está asociado a resultados negativos en salud [2].

A pesar de ello, en Argentina, y en Bahía Blanca en particular, en la práctica esta red es el producto del devenir histórico. En efecto, la decisión de apertura de muchos de los centros actualmente en funcionamiento puede ser atribuida en muchos casos al accionar de grupos de presión (como asociaciones vecinales) o a decisiones fortuitas, sin consideración alguna de las características, problemas y necesidades sanitarias de la población usuaria. Esta situación se debe a que muchas administraciones públicas no han aplicado metodologías y técnicas para localizar nuevos equipamientos o para expandir los existentes que consideren mínimos criterios de eficiencia y equidad [3].

Numerosos autores han establecido criterios que deben regir la planificación de la localización y distribución de los centros de salud. Por un lado, la red asistencial debe ser eficiente desde el punto de vista espacial, es decir, que el costo que afrontado por el conjunto de la población para encontrar atención médica (medido en distancia o en tiempo de traslado) sea el menor posible. Por otro lado, dicha red puede ser evaluada desde el punto de vista de la equidad espacial. Esta regla se refiere a la accesibilidad diferencial de un servicio por parte de los distintos grupos de población según su necesidad, y depende de la facilidad de acceso, de la variabilidad de las distancias que separan a cada individuo del centro de salud más cercano, de las características de dicho centro (especialidades brindadas, horario de atención, entre otros) y de las distintas necesidades de la población potencialmente usuaria [4].

Los denominados modelos matemáticos de localización-asignación constituyen herramientas que permiten a los tomadores de decisión aplicar los criterios de eficiencia y equidad a la planificación de una red de centros de salud. En particular, los modelos P-media suponen que, cuando la demanda no es sensible a la magnitud o calidad de los servicios suministrados en cada centro de oferta (con lo cual se puede suponer que los demandantes concurrirán al centro más cercano), la eficacia de su ubicación puede medirse a partir de la suma de las distancias de viaje entre todos los nodos de demanda y de oferta ponderada por la población de cada nodo de demanda [5].

Un problema que se inscribe en el contexto antes descripto es la asignación óptima de las localizaciones de los Centros de Atención Primaria de la Salud (CAPS) encargados de la atención primaria de la salud (APS) en Argentina. En particular, en la ciudad de Bahía Blanca (Provincia de Buenos Aires, Argentina) funcionan 49 CAPS dependientes del municipio, 45 de las cuales cuentan con atención de al menos un médico clínico y pediatra o un médico de familia. Las restantes unidades sanitarias solo cuentan con el servicio de enfermería.

A partir de lo expuesto, el objetivo general del presente trabajo consiste en evaluar la eficiencia espacial de la localización de la red actual de CAPS de la ciudad de Bahía Blanca, a partir de la comparación de las distancias estimadas en que deben incurrir actualmente el conjunto de los usuarios de los servicios de APS versus las que resultan de una asignación espacial óptima estimada utilizando un modelo de localización de tipo P-media.

2 Metodología

Para determinar la localización óptima de los centros de salud en la ciudad de Bahía Blanca se utilizó un modelo P-media con restricciones de capacidad que permite establecer cuál debería ser la ubicación de los distintos centros de oferta para minimizar la distancia total que el conjunto de la población debe recorrer para acceder a la atención médica. De esta manera, este tipo de modelo asegura que la distribución espacial de los centros de oferta cumplirá el criterio de eficiencia espacial mencionado anteriormente [6]. Luego, dado que no se dispone de información relativa a la distancia que recorre actualmente la población para acceder a los CAPS, se utilizó el mismo modelo para simular el funcionamiento del sistema, bajo el supuesto que la población acudirá siempre al CAPS más cercano.

La nomenclatura utilizada en la exposición formal del modelo se indica a continuación:

Conjuntos
- I, conjunto de nodos de demanda i
- J, conjunto de posibles localizaciones de los nodos de oferta j

Parámetros
- d_{ij}, distancia entre el nodo de demanda i y el nodo de oferta j, medido en km.
- h_i, demanda en el nodo i, medido consultas anuales.
- P, número de instalaciones a ubicar.
- $W_{máx}$, capacidad instalada de cada centro de salud abierto, medido en consultas por año.

Variables de decisión (de tipo binarias, toman valores 0 o 1)
- Y_j, toma valor 1 si el centro de oferta j se abre y 0 si el centro j no se abre.
- X_{ij} , toma valor 1 si el nodo de demanda i es asignado al centro de oferta j y 0 en caso contrario.

El modelo P-media para la determinación de la localización óptima de la red de CAPS queda determinado por las siguientes ecuaciones:

$$Min \ \sum_i \sum_j h_i d_{ij} X_{ij} \tag{1}$$

Sujeto a

$$\sum_j Y_j = P \tag{2}$$

$$\sum_j X_{ij} = 1 \qquad \forall i \tag{3}$$

$$X_{ij} - Y_j \leq 0 \quad \forall i,j \tag{4}$$

$$\sum_i h_i X_{ij} \leq W_{máx} \, y_j \qquad \forall j \tag{5}$$

$$Y_j \in \{0,1\} \quad \forall j \tag{6}$$

$$X_{ij} \in \{0,1\} \quad \forall i,j \tag{7}$$

La Ec. (1) o función objetivo, establece que se minimiza la distancia total ponderada que recorre la población de cada nodo de demanda para asistir al nodo de oferta que le es asignado. La restricción definida por la Ec. (2) determina que sólo se ubiquen P centros de oferta. La Ec. (3) asegura que cada centro de demanda i se asigna a un único centro de oferta j, mientras que la Ec. (4) establece que un nodo de demanda i será atendido por un centro de oferta j sólo si se ubica una instalación en el nodo j. La Ec. (5) impone a cada centro de salud instalado una capacidad máxima de atención. Las Ec. (6) y (7) aseguran la integrabilidad y continuidad de la solución.

2.1 Definición de conjuntos y parámetros

Los conjuntos I y J están compuestos por los 354 radios censales[1] urbanos delimitados por el Instituto Nacional de Estadísticas y Censos (INDEC) en el Censo Nacional de Población, Hogares y Viviendas del año 2010 [7]. Esto implica que cada radio censal no solo alberga un nodo de demanda, sino que también es un sitio potencial para localizar un CAPS.

La distancia d_{ij} entre cada nodo de demanda i y cada potencial sitio de radicación de un centro de oferta j se estimó utilizando *Google Maps*, considerando que la población se moviliza en automóvil o moto (con lo cual se debe respetar el sentido de circulación de las calles) y que recorre el trayecto más corto expresado en km[2]. Para estimar la distancia, se supone que toda la población está ubicada en el centroide geográfico del radio censal. En el caso de la ubicación de los centros de salud, se adoptaron dos criterios: si en el radio censal está funcionando un CAPS, se respeta la ubicación real actual; mientras que en el resto de los casos (radios censales que no albergan ningún CAPS en la actualidad) la ubicación potencial de los centros se considera dada por su centroide geográfico.

La información estadística referida a las consultas históricas realizadas en cada CAPS puede no reflejar la verdadera necesidad de los habitantes de cada radio censal, ya que no toda necesidad se traduce en una demanda efectiva al sistema de salud debido a diversas barreras al acceso [8]. Por lo tanto, la utilización de dicha información en el modelo podría perpetuar las desigualdades preexistentes en el acceso a los servicios de APS. Además, si bien se cuenta con información de las consultas atendidas por cada CAPS existente, no se dispone de datos respecto del radio censal de procedencia de los usuarios atendidos. En vista de estas restricciones, la demanda de consultas de cada radio censal, h_i, se determinó ponderando el número de residentes de cada radio por un índice de nivel socioeconómico[3] estimado para cada nodo de demanda [7]. Más específicamente, se asumió que las puntuaciones del índice socioeconómico calculado para cada radio censal reflejan la demanda normativa (promedio) de las consultas médicas anuales por habitante. De esta forma, la población que habita en

[1] El radio censal es la unidad censal más pequeña utilizada por el INDEC en el CENSO 2010

[2] Para esta estimación se programó una macro en Excel donde se cargaron las coordenadas de cada elemento de los conjuntos *I* y *J* y que se vinculaba automáticamente a G*oogle Maps* para el cálculo de las distancias.

[3] El índice se construyó aplicando análisis factorial a la información estadística relativa a las características habitacionales, del hogar y de la población relevada en el CENSO 2010. Para mayor detalle consultar Arnaudo [11].

aquellas áreas geográficas con mayores niveles de desventaja presenta mayores necesidades de atención de la salud [9, 10]. El objetivo de este procedimiento es estimar una demanda *potencial* de consultas médicas, y no la demanda real, introduciendo en el análisis un criterio de equidad en el acceso a la atención médica al priorizar (en términos de facilidad en el acceso a los CAPS) a la población con mayor necesidad de atención médica. Por último, dado que la información relativa a la cantidad de habitantes de cada radio censal data del Censo 2010, el número de habitantes de cada radio censal utilizado en los cálculos se actualizó teniendo en cuenta la tasa de crecimiento poblacional informada por INDEC y suponiendo que la misma se distribuye uniformemente por toda la ciudad.

Con el objetivo de poder comparar la localización óptima que resulta de cada uno de los modelos con la situación actual se considera que se instalarán 45 (P=45) centros de oferta (no se consideran los 4 CAPS que cuentan solo con atención de enfermería). Esto implica suponer que todos los centros de salud a instalar cuentan con la atención de un médico de familia o la combinación de un médico clínico y un pediatra.

La capacidad máxima de atención de cada CAPS se estima en 5.000 consultas por año. Tal capacidad máxima se determinó asumiendo que los centros funcionan 5 horas diarias, igual que los CAPS que actualmente se encuentran funcionado y que cada consulta médica insume 20 minutos [12].

2.2 Escenarios de Estudio

Además del caso base, el modelo se utiliza para analizar distintos escenarios, construidos a partir de valores alternativos para dos parámetros: i) el número de centros de salud a instalar (P) y ii) la capacidad máxima de atención de los CAPS ($W_{máx}$) (Tabla 1). Para la elaboración de estos escenarios se consideraron diversas manifestaciones públicas por parte de representantes del gobierno local a cargo de su gestión al momento de desarrollar esta investigación, en las cuales afirmaron su intención de reforzar la dotación de recursos humanos de algunos centros de salud estratégicamente ubicados, y de cerrar aquellos centros que presentan alta capacidad ociosa.

Tabla 1. Escenarios Propuestos. Valores de la capacidad máxima de atención de cada CAPS ($W_{máx}$) y Número de CAPS a instalar (P)

	$W_{máx}$ (cant. de consultas)	P (Núm. de CAPS)
Caso Base	5.000	45
Escenario 1	5.000	44
Escenario 2	5.000	43
Escenario 3	7.500	45
Escenario 4	7.500	44
Escenario 5	7.500	43

Fuente: Elaboración propia

Todos los escenarios se construyen con el fin de evaluar el efecto de cambios en los parámetros sobre la distancia óptima recorrida por la población para acceder a un centro de salud. Los escenarios Caso Base, 1 y 2 analizan el impacto de la disminución en la cantidad de CAPS. Mientras que, los escenarios 3-5 mantienen abierta la

misma cantidad de centros que los primeros escenarios y al mismo tiempo aumentan la cantidad de consultas que se pueden atender.

En la actualidad no existen datos respecto de las distancias efectivamente recorridas por los residentes de cada radio censal de la ciudad de Bahía Blanca para recibir atención en un CAPS. Dado que tal información resulta necesaria para comparar la performance de la red actual de CAPS en relación a las soluciones óptimas propuestas por el modelo, la misma se estimó utilizando el mismo modelo y considerando como dadas las localizaciones de los CAPS. En este caso, el modelo se limita a asignar la población de cada nodo de demanda a un centro de salud, cumpliendo con las restricciones impuestas y minimizando la distancia recorrida. En este mismo sentido, dado que tampoco se cuenta con información acerca de la capacidad máxima de atención de cada centro de salud, y con el fin de que la comparación de la situación actual con los escenarios óptimos sea consistente, se supone que cada CAPS instalado en la actualidad atiende como máximo 5.000 consultas al año. Este supuesto se sustenta en las horas de atención de los CAPS que actualmente están funcionando.

Para el análisis de los resultados, cómo medida de la eficiencia espacial de cada solución se considera, la distancia total recorrida en el sistema (valor de la función objetivo), entendiendo que a medida que esta distancia disminuye la distribución de los centros de oferta mejora la eficiencia espacial. Además, en cada solución se tiene en cuenta dos indicadores de desempeño adicionales: la distancia que en promedio se debe recorrer para acceder a una consulta médica y la distancia máxima que debe recorrer un usuario para arribar a un CAPS.

3 Resultados

El modelo de localización óptima se implementó y resolvió en GAMS [13] con el *solver* CPLEX*,* ejecutado en una computadora portátil con procesador Core i5 (4° generación) de 1.2GHz y 6GB de memoria DDR3. Los tamaños de las diferentes instancias del modelo, en todos los escenarios, fueron de 126.025 variables (todas binarias), 355 restricciones de igualdad y 126.025 restricciones de desigualdad. Además, todos los escenarios se resolvieron en menos de 90 segundos.

En la Figura 1 se muestran los resultados del cálculo del índice socioeconómico de por radio censal y la ubicación actual de los CAPS. Para facilitar la exposición de los resultados, se dividió a los radios censales en cuartiles, donde el primer cuartil comprende al 25% de los radios censales analizados con mayor nivel socioeconómico en términos relativos y el cuarto cuartil incluye al 25% de los radios censales con menores valores de dicho índice. Se aprecia que los radios censales con menor nivel socioeconómico son los situados en la periferia de la ciudad, lo cual parece corresponderse con la mayor oferta de CAPS existentes en los mismos. Sin embargo, esta correspondencia que a simple vista pareciera presentarse entre la ubicación actual de los CAPS y las necesidades de atención sanitaria (estimadas a partir del índice de nivel socioeconómico) no necesariamente implica que la distribución actual de la red de centros de atención primaria resulte eficiente desde el punto de vista espacial. Para poder ser concluyentes al respecto, a continuación, se exponen los resultados de la simulación de la situación actual, así como de la resolución del modelo matemático de localización óptima bajo los escenarios planteados.

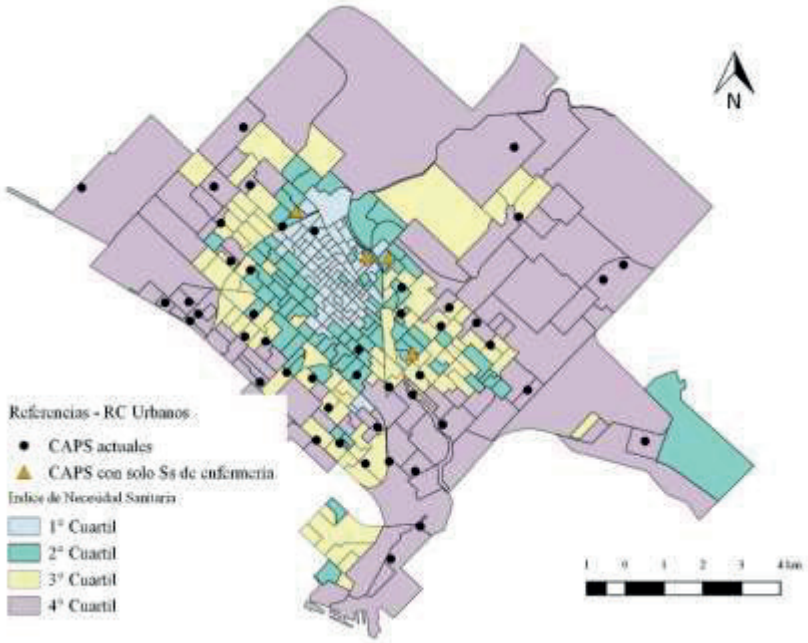

Fig 1. Bahía Blanca. Radios Censales agrupados por cuartiles del índice de necesidad sanitaria y distribución actual de CAPS (Fuente: Elaboración propia en el software QGIS [14])

Un primer resultado a resaltar es que cuando se simula la situación actual, el modelo no asigna población a uno de los CAPS en funcionamiento. Es decir, el modelo infiere que con los parámetros usados en esta corrida el mismo no es necesario. Por otra parte, en todos los escenarios posibles no hay diferencias significativas en las soluciones encontradas en cuanto a la localización de los CAPS instalados. Además, si bien existe correspondencia entre las necesidades de salud y la ubicación actual de los CAPS, de acuerdo con las soluciones óptimas encontradas en cada escenario solo el 12% de los CAPS actuales está situado óptimamente (Figura 2).

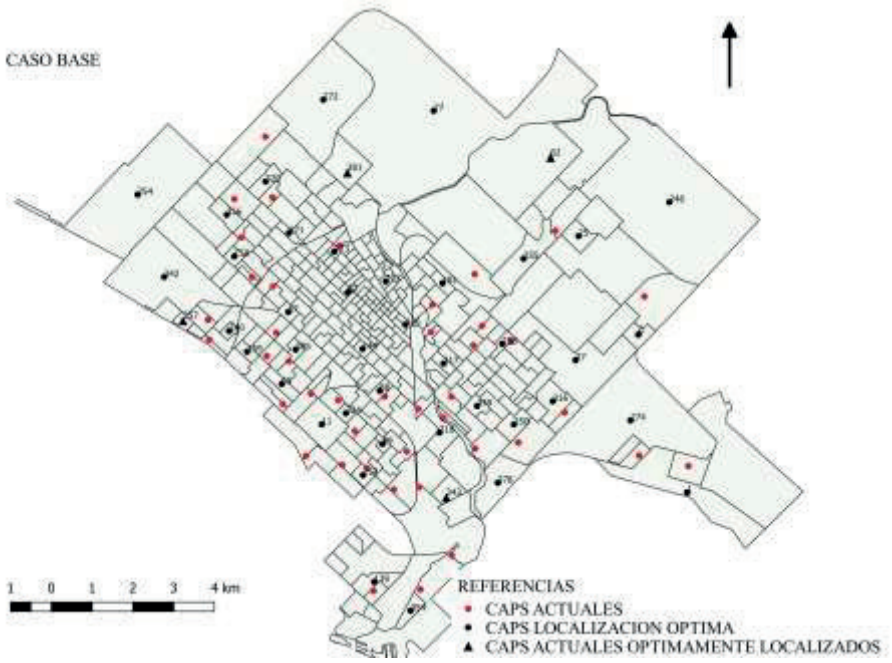

Fig 2. Bahía Blanca. Localización óptima de los CAPS (caso base) versus localización actual (Fuente: Elaboración propia en el software QGIS [14])

Como se mencionó anteriormente, para evaluar las distintas soluciones desde el punto de vista de la eficiencia espacial, es necesario comparar para cada uno de los escenarios propuestos la distancia recorrida por la población para acceder a un CAPS. En la Tabla 2 se observa que cuando se compara la situación actual simulada con el caso base, se observa que una reorganización de la red asistencial podría reducir las distancias recorridas, tanto la distancia total recorrida en el sistema como la distancia promedio por consulta, aproximadamente un 36%. Además, la distancia máxima que debe recorrer quien vive más alejado de un CAPS se reduce en un 50%.

Tabla 2. Distancias recorridas para concurrir a un CAPS (en km)

	Total Sistema	**Promedio**	**Máxima**
Situación Actual	157.674	1,04	4,18
Caso Base	100.733	0,66	2,10

Fuente: Elaboración propia.

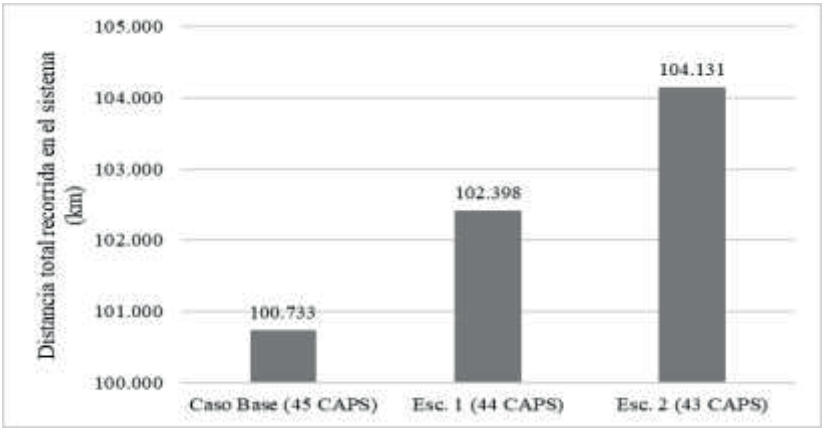

Fig 3. Análisis de escenarios. Distancia total recorrida (km). Máxima capacidad de atención 5.000 consultas por año (Fuente: Elaboración propia).

Un resultado esperable se verifica en el resto de los escenarios. Si disminuye el número de CAPS abiertos (manteniendo la capacidad de atención en 5.000 consultas anuales) aumenta la distancia total recorrida del sistema, pero por una cantidad muy pequeña (3,5% al cerrar dos centros de salud en relación con el caso base) (Figura 3). Del mismo modo, aumentar la capacidad de atención de los CAPS en un 50% reducirá las distancias de viaje (Figura 4). Sin embargo, comparando las Figuras 2 y 3 se aprecia que la reducción en los tiempos de viaje atribuible al aumento de la capacidad es de una magnitud no significativa. Es decir, que aumentar los costos de funcionamiento de los CAPS no representaría una mejora sustancial en términos de eficiencia espacial.

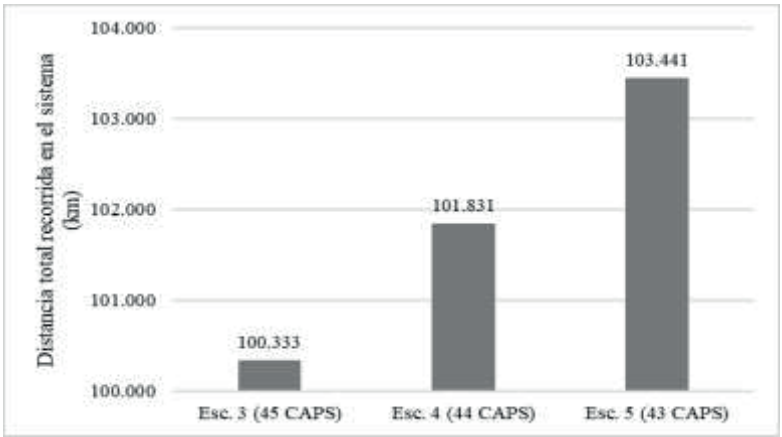

Fig 4. Análisis de escenarios. Distancia total recorrida (km). Máxima capacidad de atención 7.500 consultas por año (Fuente: Elaboración propia).

4 Discusión y conclusión

El presente trabajo se propuso analizar la eficiencia de la disposición espacial de la red de CAPS del subsector público de la salud de la ciudad de Bahía Blanca. La relevancia de este análisis se justifica por la existencia de numerosos estudios que han demostrado que las distancias que deben recorrer los potenciales usuarios puede ser decisiva al momento de facilitar (y asegurar) su concurrencia a los centros de salud. En este sentido, una asignación espacial incorrecta puede disminuir la efectividad de las políticas de APS, lo cual en última instancia se traduce en un menor estatus de salud poblacional y/o en mayores costos para el sistema de salud, dado la necesidad de atender situaciones de enfermedad que podrían haber sido prevenidas o atenuadas en sus consecuencias.

Los resultados del modelo indican que una relocalización de la red de CAPS redundaría en una disminución del 36% de las distancias recorridas por la población, tomando como referencia el caso base que es uno de son los que arroja los mejores resultados. De esta manera una reorganización de la red prestacional implicaría una mejora en términos de eficiencia espacial. Así, con igual presupuesto operativo se mejoraría la situación de la población. Asimismo, comparando la situación actual con los escenarios en los que se instalan una menor cantidad de CAPS y se supone igual capacidad máxima de atención que en actualidad (escenario 1 y 2), se evidencian que se podrían lograr mejoras en la eficiencia espacial del sistema con menores costos de funcionamiento para el sistema de salud. Por otro lado, los escenarios que implican un aumento de la capacidad máxima de atención y por lo tantos mayores costos de funcionamiento generan resultados similares a los escenarios de bajos costos. Cabe mencionar que este análisis no tiene en cuenta los costos asociados a la relocalización de los centros de salud.

Si bien el eje del trabajo es la eficiencia espacial, el análisis realizado también incorporó implícitamente un objetivo de equidad en el acceso a los servicios de salud, en la medida que se dio mayor ponderación a los nodos de demanda con más alto porcentaje de población en condiciones de vulnerabilidad socioeconómica. En efecto, el procedimiento utilizado para estimar la demanda, al intentar captar la necesidad de consultas médicas y no las consultas efectivamente registradas introduce un elemento de equidad en el análisis. Este enfoque, aunque discutible (como todo aporte de carácter normativo) cuenta con antecedentes en la literatura (Australian Institute of Health and Welfare [9]). Una restricción adicional derivada de este enfoque es la imposibilidad de validar las estimaciones de demanda (ya que estas no necesariamente se corresponderán con los datos observados, y de hecho no se espera que sea así). Sin embargo, los resultados obtenidos son similares a los encontrados por Elorza et al [15] a través de una metodología diferente también aplicada a la ciudad de Bahía Blanca.

Otros autores han utilizado los modelos P-media para determinar la localización óptima de CAPS. Las principales diferencias de estos estudios con el que se presenta en este trabajo radican en i) la forma de estimar la demanda de los CAPS y ii) en que estos autores implementaron sus problemas en diversos *softwares* pertenecientes a los denominado sistemas de información geográficos (SIG) [1,16]. Respecto de la estimación de demanda, Fo y Mota [1] estiman la cantidad necesaria de CAPS suponiendo que debe existir un centro cada 12.000 habitantes. Mientras que Ramírez [16] su-

pone que la población que acude a los CAPS es solo aquella que no cuenta con cobertura de salud por parte de una obra social o una empresa de medicina prepaga.

Al momento de valorar las conclusiones, las limitaciones del análisis deben ser tenidas en cuenta. En primer lugar, las distintas soluciones del modelo suponen la posibilidad de relocalizar todos los CAPS actuales, situación que difícilmente se verifique en la realidad. En segundo lugar, las distancias recorridas actualmente por la población para acceder a los centros de salud tuvieron que ser simuladas, bajo el supuesto de que siempre se acude al CAPS más cercano. Evidentemente esto no necesariamente es un fiel reflejo de la realidad, en la medida que los habitantes tengan la posibilidad de elegir libremente el centro donde se desean atender. Sin embargo, se optó por esta vía dado que la información de las distancias efectivamente recorridas no se encuentra disponible. En tercer lugar, debe considerarse que implícitamente se asumió que la calidad de atención ofrecida por cada CAPS, así como los horarios de atención es idéntica, de forma tal que la elección del centro de oferta por parte de los usuarios solo dependerá de la distancia a recorrer. Por último, solo se considera que la población se traslada en un vehículo particular siendo deseable incorporar la posibilidad de que se desplace en transporte público o peatonalmente.

El trabajo puede ser ampliado en diversas direcciones. Una alternativa evidente sería estimar las distancias recorridas en la actualidad a partir de un estudio de campo, tomando una muestra de la población que concurre a los CAPS de la ciudad y registrando su lugar de residencia. Otra posibilidad consiste en postular una función de probabilidad de concurrencia a los CAPS en función de la distancia que debe recorrer los residentes de cada nodo, donde mayores distancias estarían asociadas a menores probabilidades de concurrencia. Por último, el modelo podría ser modificado para incluir la probabilidad que la población utilice medios de transporte alternativos.

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Comparación de Métodos Multicriterio Grupales: Procesos DRV vs AHP grupal. El caso de la gestión sobre residuos patógenos

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Resumen Ante la necesidad de las organizaciones de afrontar diversos problemas de gestión, la toma de decisiones multi–criterio grupal ha crecido como campo de estudio. Aún así, existen dificultades no resueltas en la aplicación de estas metodologías relacionadas con la valoración del nivel de consenso alcanzado y el tratamiento de las formas de ignorancia sobre la información disponible (imprecisión, incertidumbre y falta de datos). En consecuencia, el presente trabajo evalúa y compara, al considerar las cuestiones antes mencionadas, dos métodos de toma de decisiones multi–criterio grupales: uno denominado Procesos DRV (Decisión con Reducción de Variabilidad) y otro conocido como AHP grupal (proceso analítico jerárquico grupal). La propuesta se aplicó a un caso real referido al problema de selección de proveedores para la gestión de residuos patógenos en una institución pública. En las conclusiones se reconocen las principales diferencias entre las dos metodologías analizadas, se indican las limitaciones del caso y se anticipan futuras líneas de investigación.

Keywords: Métodos multi–criterio grupales, PROCESOS DRV, AHP GRUPAL, Gestión de residuos patógenos

1. Introducción

Con el traslado y transferencia de los métodos de investigación operativa al campo industrial y de los negocios, se presentaron variedad de nuevas cuestiones a investigar. El campo de la decisión multi–criterio discreta no fue la excepción,

ya que del estudio de métodos individuales, se desprendió el interés por estudiar los métodos grupales [1].

Uno de los espacios de aplicación, que ha crecido junto con las población mundial es el uso de herramientas multi–criterio para la adecuada gestión de los residuos que se generan en el diagnóstico, tratamiento e inmunización de seres humanos o animales [2]. De hecho, la literatura especializada remarca que aunque el valor de los estudios de gestión de residuos patógenos en los países en desarrollo es claro, unos pocos estudios abordan directamente el problema en el contexto Latinoamericano [3]. En particular, la gestión de este tipo de residuos, no es carente de dificultades y es afectada por una multiplicidad de factores y actores que la administran. Kharat et. al. [4] señala que la gestión involucra un proceso complejo debido a que interactúan diversas dimensiones como: medioambiente, presupuesto, gestión pública, diversidad de actores, por mencionar algunos.

El proceso de asistencia para la toma de decisiones de por sí es complejo porque debe considerar la naturaleza del problema, su campo de aplicación y obtiene las preferencias del tomador de decisiones [5]. Desde que se formaliza el estudio de los métodos que soportan las decisiones en problemas grupales se señala que la complejidad es creciente porque es necesario considerar las preferencias de los diferentes grupos de interés [6].

En un análisis bibliométrico sobre los métodos grupales Kabak y Ervural [7], resaltan que el estudio de tales métodos ha crecido en los últimos años y que a pesar de su crecimiento pocos trabajos se ocupan de analizar el grado de consenso alcanzado. Más aún, la comparación entre métodos que trabajan con medidas de consenso es menos abordada todavía por la literatura.

Paralelamente, la aplicación de estas metodologías no está exenta de ciertas dificultades sobre la información disponible conocidas como formas de ignorancia. Entre las formas de ignorancia se encuentra la incertidumbre o datos que inducen alguna forma de conocimiento parcial o creencia por parte del observador, la imprecisión o error de medición y falta de disponibilidad sobre ciertos datos [8; 9]

Las consideraciones conjuntas sobre el nivel de consenso logrado y la contemplación de los efectos sobre las formas de ignorancia no ha sido documentada. Con el objetivo de superar estas dificultades, este trabajo estudia compara el grado de consenso alcanzado y el tratamiento sobre las formas de ignorancia de dos métodos de toma de decisiones multicriterio grupales: uno denominado Procesos DRV (Decisión con Reducción de Variabilidad)(Zanazzi, 2016 [10]) y otro conocido como AHP (Proceso Analítico Jerárquico) grupal (el cual es uno de los más populares métodos multi–criterio) [11]. Para la comparación ambos métodos se trabaja sobre un caso real referido a la gestión de residuos patógenos.

En cuanto a la estructura de este documento, se continúa con un apartado de referencias teóricas relevantes, donde se recorren tanto metodologías multicriterio para la toma de decisiones en grupo comparadas en este trabajo. A continuación, se presentan los resultados obtenidos y se discuten los hallazgos. El trabajo cierra con las conclusiones obtenidas, además de especificar limitaciones y líneas de investigación futuras.

2. Referencias relevantes

2.1. Procesos DRV en la literatura

El método Procesos DRV (Decisión con Reducción de Variabilidad)es una aproximación que busca reducir las dificultades en la información que afectan a los procesos de decisión grupal (incertidumbre, imprecisión, datos inexistentes) [10].
El método Procesos DRV puede aplicarse con problemas que requieren elegir un objeto entre una cantidad finita de alternativas. Además se supone que los miembros del grupo comparten objetivos en cuanto al problema analizado, es decir que no se trata de situaciones de negociación o de conflicto [12; 13].
El método se desarrolla en tres etapas: Estabilización; Agregación y Ordenamiento. La secuencia de operaciones es la siguiente:

- Fase Estabilización: permite que el grupo analice en plenario los diferentes sub–problemas que integran el proceso decisorio y se establezca un nivel de consenso básico. Incluye:
  - Estructuración del problema: Se esquematiza el problema en un diagrama tipo árbol, y que puede dividirse en sub–problemas: asignación de prioridades a los criterios, asignación de utilidades a las alternativas según el primer criterio, asignación de utilidades según el segundo criterio y así sucesivamente.
  - Estudio de un sub–problema: es necesario analizar uno por uno, los distintos subproblemas. Respecto de cada subproblema, las percepciones de los integrantes pueden ser completamente distintas, porque cada persona filtra la realidad de forma selectiva en función de su área de conocimiento y experiencias anteriores [14].
  - Análisis grupal del sub–problema: se realizaron ejercicios para la reducción de diferencias de posturas que permiten definir los elementos a comparar en el sub–problema e intercambiar conocimientos.
  - Asignación de utilidades a los elementos comparados: se realiza una actividad destinada a valorar si el consenso es real o es solo aparente. Para ello, se solicita que los miembros del grupo asignen, de manera individual y con absoluta independencia unos de otros, utilidades de tipo subjetivo a los elementos comparados [15].
  - Análisis de las utilidades: El método supone que si el grupo mantiene diferencias importantes, las utilidades deben ser muy diferentes y están representadas por la Distribución Uniforme. El trabajo grupal debe contribuir a reducir las diferencias, por lo que la dispersión observada debe mostrar una tendencia sostenida a la reducción. De este modo, para verificar la estabilidad y el consenso se trabaja con el Indicador IVR (Índice de Variabilidad Remanente, ver expresión 1[5]) y el análisis de normalidad

[5] El IVR compara a través de un cociente la variabilidad de las utilidades asignadas por el grupo en relación a las utilidades representadas por la distribución uniforme. Aquí, k representa el elemento comparado, u^*_{kn} muestra la utilidad asignada por el

de los datos mediante el test de Shapiro-Wilks modificado por Rahman y Govindarajulu [16].

$$IVR = \frac{\sum_{k=1}^{K}\sum_{n=1}^{N}(u_{kn}^{*} - \bar{u_k^{*}})^2}{\frac{N-1}{3k}} * 100\,\% \tag{1}$$

- Verificación de consenso: cuando todas las utilidades asignadas a cada uno de los elementos comparados, pudieron ser representadas con una Distribución Normal, fue posible presumir consenso y pasar a un nuevo su–problema (Segundo ítem).

- Fase Agregación permite obtener valores globales para cada alternativa de decisión. Para la obtención de coeficientes globales se trabaja con la ponderación lineal. Así, W_j es la variable aleatoria que representa los pesos de los criterios, y las U_{ij} son variables aleatorias que simbolizan las utilidades asignadas a los candidatos al evaluar la alternativa genérica i bajo el criterio j. La contribución parcial a la prioridad asignada se obtiene como el producto de las dos variables aleatorias mencionadas conforme a la expresión 2.

$$Z_{ij} = W_j * U_{ij} \tag{2}$$

Asimismo, los valores globales de una alternativa genérica V_i, se obtienen como se indica en 3.

$$V_i = \sum_{i=1}^{J} W_j * U_{ij} = \sum_{i=1}^{J} Z_{ij} \tag{3}$$

- Fase ordenamiento permite ordenar las alternativas, desde la mayor a la menor preferencia. La comparación de los promedios de las valoraciones V_i permite establecer un primer ordenamiento de la mayor a la menor preferencia. Sin embargo, dado que los valores observados pueden estar afectados por el error muestral, es posible que esta modalidad conduzca a identificar relaciones de preferencia que no son reales. Para distinguir estas situaciones el método aplica pruebas repetidas de comparación de variables dependientes y controla la tendencia a cometer errores de tipo I, con la tasa de descubrimiento falso propuesta por Benjamini y Yekutieli [17].

2.2. AHP grupal en la literatura

Existen múltiples antecedentes de adaptación de AHP a la toma de decisiones grupales [11]. Un artículo seminal es el presentado por Forman y Peniwati [18] donde dos métodos son propuestos para sustanciar las modalidades grupales de trabajo: la primera consiste en la Agregación de juicios individuales (AIJ) y la segunda plantea la Agregación de prioridades individuales (AIP).

participante n al comparar el elemento genérico k, $\bar{u_k^{*}}$ es la utilidad promedio considerada por el grupo al considerar el elemento k y N expresa el total de participantes del grupo.

La literatura acuerda que la estrategia AIP transforma las matrices de comparación por pares individuales por medio del método de la media geométrica en una matriz de comparación grupal y asume el grupo como una unidad sinérgica. La estrategia AIJ se aplica cuando los miembros del grupo tienen diferentes sistemas de valores y la agregación de prioridades individuales se puede calcular al utilizar una media geométrica o media aritmética para que el vector de prioridades individual se transforme en un vector de prioridad grupal [18].
Dong y Saaty [19] hacen una propuesta superadora basada en un modelo de búsqueda de consenso asistido por un moderador. En este enfoque, agregan los juicios individuales con la estrategia AIJ e introducen una medida llamada Índice de consenso grupal (GCI) que refleja la compatibilidad de la matriz propuesta por un participante genérico p en relación con la matriz grupal. Si el GCI no identifica la compatibilidad deseada del participante en relación con el grupo, el moderador sugiere al experto más discordante para acercar su posición al grupo. En una contribución más reciente, Dong y Cooper [20] introduce una innovación para estimar los pesos que se asignarán a cada miembro del grupo a través de las cadenas de Markov. Además, se incorpora un mecanismo de retroalimentación como sustituto de las sugerencias del moderador para minimizar el sesgo de subjetividad en el momento en que aconseja a los expertos sobre cómo revisar o actualizar sus opiniones.

De ahora en adelante, la propuesta de Dong y Saaty [19] se utilizará para comparar con el método de procesos DRV. La justificación de esta elección radica en que los procesos DRV utilizan la figura de un facilitador.

El procedimiento de Dong y Saaty [19] toma las matrices de todos los tomadores de decisiones con una consistencia aceptable para construir una matriz grupal. Cada una de las valoraciones grupales es obtenida a través de la expresión 4.

$$a_{ij(g)} = \prod_{p=1}^{N} (a_{ij_{(p)}})^{\rho_p} \tag{4}$$

dónde N es el número total de participantes, ρ_p es el pero de la opinión de cada experto y se verifica que $\sum_{p=1}^{N}(\rho_p) = 1$.

Luego, se calcula el índice GCI (que la compatibilidad de cada decisor individual en relación al grupo) para cada uno de los N participantes. La ecuación que refleja el GCI para cada participante p es introducida en 5.

$$GCI_k = \frac{1}{k^2} \sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij_{(p)}} a_{ji(g)} \tag{5}$$

dónde k es el número de elementos comparados cada vez, $a_{ij_{(p)}}$ es cada una de las valoraciones de la alternativa i bajo el criterio j de un participante genérico p, and $a_{ji_{(g)}}$ corresponde a la valoración del criterio j bajo la alternativa i para el grupo.

Si el GCI de cada uno de los N participantes es menor o igual a ϵ (ϵ puede fijarse en un 1.01); se puede decir que el decisor genérico p tiene un aceptable

consenso y entonces el proceso se detiene. Por el contrario, si el GCI excede el umbral, el método calcula la media geométrica entre la posición del tomador de decisión más discordante (máximo GCI) y la matriz grupal. Luego, el moderador propone al tomador de decisión, una nueva valoración que surge del cálculo anterior para acercarlo a la posición del grupo que puede ser representada por la expresión 6.

$$a_{ij(p)}^{t+1} = {a_{ij(p)}^{t}}^{\alpha^t} \cdot {a_{ij(q)}^{t}}^{(1-\alpha^t)} \tag{6}$$

(Aquí, el α es sugerido por el moderador, mide el grado en que el decisor mantiene su postura y puede variar en el rango entre 0 y 1. Paralelamente, su complemento $(1-\alpha)$ representa el nivel de acercamiento de la posición del decisor a la posición grupal).

Si el tomador de decisiones más alejado rechaza la propuesta, no puede actualizar sus juicios en cualquiera de las siguientes iteraciones. De esta manera, su evaluación en las próximas iteraciones, tendrá resultados obtenidos a través de la expresión 7.

$$a_{ij(p)}^{t+1} = a_{ij(p)}^{t} \tag{7}$$

El proceso antes mencionado se repite con las nuevas valoraciones del participante más discordante en la ronda t + 1 y se construye la nueva matriz de grupo. Nuevamente, el GCI de cada participante se evalúa de forma iterativa hasta que se den alguna de las siguientes condiciones:

- el GCI de cada participante es menor que el umbral de 1.01.
- se da una situación dónde todos los expertos se han negado a actualizar sus valoraciones.
- o se ha alcanzado el número máximo de iteraciones. Cabe señalar que el moderador sugiere subjetivamente el número límite de iteraciones permitidas.

3. Resultados y discusión

Se analiza el caso de la selección de proveedores para el recolección, tratamiento y disposición final de los residuos patógenos en una institución universitaria pública. El caso fue resuelto con el método procesos DRV en su aplicación original.

Para valorar a los tres candidatos que se presentaron para prestar el servicio (Oferente 1, Oferente 2 y Oferente 3), las actividades de estructuración permitieron adoptar los siguientes criterios: modalidad operativa y logística (MO), mejora del servicio (MS), costo (CO), tratamiento y disposición final de los residuos (TR), experiencia (EXP), flota de vehículos (FLO) y condiciones de higiene y seguridad (HyS). La figura 1 representa el diagrama de árbol del problema

En la aplicación inicial el estudio del sub–problema referido a determinar los pesos criterios y los subproblemas MO, CO y EXP requirieron dos iteraciones de análisis. Adicionalmente, el análisis del subproblema FL requirió 3 iteraciones

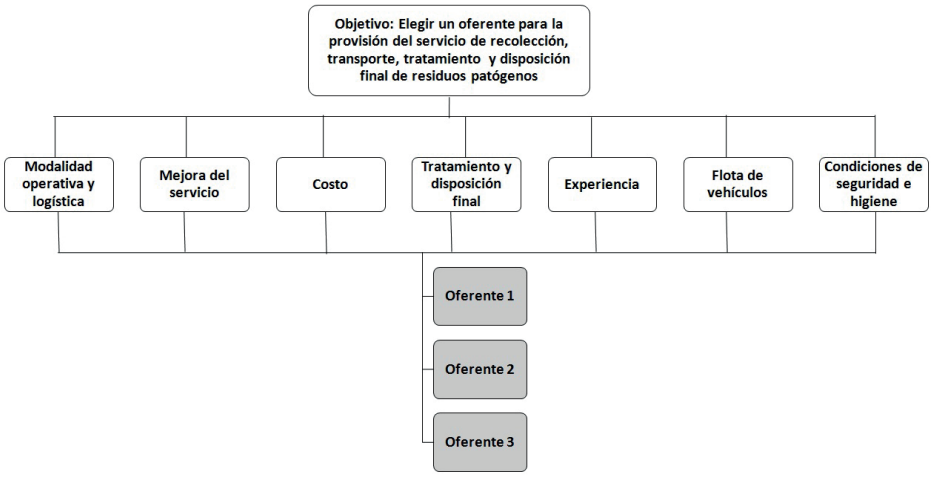

Figura 1. Diagrama de árbol del problema

de análisis y los restantes sub–problemas (MS,HyS y TR) requirieron sólo una iteración.

En los casos donde se precisaron varias iteraciones, se observa que la suma de cuadrados refleja los niveles de incertidumbre e imprecisión que afectan al proceso de decisión. Es decir, en la medida que el IVR decrece, la suma de cuadrados observada (numerador del IVR) decrece y en las diversas iteraciones se aprecia cómo se controlan las dificultades sobre la información. Es pertinente destacar en este punto, que cuando el acuerdo era aparente y aún quedan pendientes nuevas iteraciones, la información se presenta a los miembros del grupo a través de diagramas de caja de las utilidades estandarizadas con lo que es sumamente dificultoso dilucidar quién es el actor en desacuerdo.

Luego, cuando el IVR estuvo por debajo del umbral permisible para todos los sub–problemas, las pruebas de normalidad resultaron aceptables. Lograda la estabilidad, los pesos resultantes fueron de: $0,302$, $0,224$, $0,136$, $0,117$, $0,079$, $0,076$ y $0,066$ para los criterios MO, CO, EXP, FLO, MS, HyS y TR, respectivamente.

Los valores promedio globales para cada alternativa, fueron $0,44$, $0,38$ y $0,18$ para los oferentes uno, dos y tres respectivamente. Como las diferencias entre los oferentes uno y dos pueden originarse en el error muestral, se aplicaron pruebas de comparación de medias, arrojando los resultados que se presentan en el cuadro 1. Allí se obtienen diferencias significativas entre los oferentes.

En la tabla 1, el valor p de contraste se obtiene mediante la aplicación del algoritmo de Benjamini y Yekutieli [17]. Cuando el valor p observado en la prueba es menor que el valor de contraste la diferencia se considera significativa. En este caso hay preferencia estricta de la alternativa uno con las restantes.

Los datos recopilados de la primera evaluación realizada por los participantes

Tabla 1. Ordenamiento final.

Oferentes comparado	Valor t	Valor p observado	Valor p de contraste	Decisión
1 con 2	4,68	0,00545	0,00909	Hay Diferencia
1 con 3	19,4	0,00001	0,01819	Hay Diferencia
2 con 3	16,07	0,00002	0,02728	Hay Diferencia

al aplicar los procesos DRV son adaptados para trabajar con AHP grupal en la versión propuesta por Dong y Saaty. Así, las utilidades asignadas en la primera iteración por los participantes fueron tomadas para calcular cocientes de modo que las valoraciones se transformen en una comparación por pares. De este modo, se obtienen matrices triangulares y con ellos se aplica el modelo de consenso propuesto por Dong y Saaty [19].
Se simularon dos situaciones: una en la que la sugerencia del moderador de acercarse a la postura más discordante a la posición del grupo se acepta la mayor parte del tiempo y otra, en la que en la primera iteración el participante más discordante rechaza la sugerencia del moderador para acercarse a la posición global.
Adicionalmente, Dong y Saaty [19] proponen que α indica qué tan detallado será el análisis grupal en la búsqueda de consenso. Se trabajará en todas las iteraciones con un α de 0,5. El método citado permite trabajar con pesos diferenciales para los diferentes tomadores de decisiones. En esta línea, la posibilidad de asignar diferentes pesos a cada participante puede acentuar el efecto de la presión de grupo y considera una posición más fuerte que otra. En este ejemplo, para fines de comparabilidad con los procesos DRV, se utilizaron pesos idénticos para todos los tomadores de decisiones en todas las iteraciones.
Los resultados que se refieren a la aceptación mayoritaria de la sugerencia del moderador se resumen en la Tabla 2 y la Tabla 3. En contraste, los resultados vinculados a la segunda situación simulada de rechazo de la sugerencia del moderador en la primera ronda se resumen en la Tabla 4 y la Tabla 5

Del análisis de la Tabla 2 preparada con el método AHP y con un nivel α de 0.5 puede apreciarse que 58 iteraciones son necesarias para obtener la matriz grupal. En paralelo, la tabla 4 elaborada con un nivel α de 0,5 muestra 68 iteraciones. De este modo, se destaca que el número de iteraciones aumenta a medida que el tomador de decisiones más discordante se niega a actualizar sus valoraciones en las primeras rondas. Este aumento en el número de intercambios puede ser valorado por el grupo como una instancia negativa y, por lo tanto, condiciona futuras aplicaciones. Asimismo, se observa que el método facilita mejorar el nivel de consenso al aumentar el número de rondas.

En el procedimiento AHP, aunque la actividad es grupal, no se indica en el artículo de Dong y Saaty [19] que se tomen precauciones para recopilar las evaluaciones subjetivas de manera independiente, con lo cual el impacto del la presión grupal puede imponer sesgos. Además, la sugerencia del moderador sobre el participante más discordante puede aumentar esa desviación y condicionar su posición para avanzar y finalizar la actividad.

Tabla 2. Índice de consenso grupal (GCI) y la elección del tomador de decisiones más discordante para cada subproblema en la situación I

Sub-problema	Iteración	Índice de consenso grupal (GCI)	Decisor más discordante (DM_P)	Elección
Peso del criterio	0	$GCI_0 = (1{,}0596; 1{,}009; 1{,}0221; 1{,}0163; 1{,}0012; \mathbf{1.0744})$	DM6	Acepta
	1	$GCI_1 = (\mathbf{1.0539}; 1{,}0085; 1{,}0225; 1{,}0146; 1{,}0038; 1{,}0227)$	DM1	Acepta
	2	$GCI_2 = (1{,}0167; 1{,}0073; 1{,}02; 1{,}0185; 1{,}0029; \mathbf{1.0209})$	DM6	Acepta
	3	$GCI_3 = (1{,}0152; 1{,}0061; \mathbf{1.0193}; 1{,}0171; 1{,}0036; 1{,}0048)$	DM3	Acepta
	4	$GCI_4 = (1{,}0132; 1{,}0076; 1{,}0043; \mathbf{1.0141}; 1{,}0031; 1{,}0045)$	DM4	Rechaza
	5	$GCI_4 = (\mathbf{1.0132}; 1{,}0076; 1{,}0043; \mathbf{1.0141}; 1{,}0031; 1{,}0045)$	DM1	Rechaza
Criterio Modalidad Operativa	0	$GCI_0 = (1{,}0458; 1{,}3479; 1{,}0212; 1{,}0543; 1{,}037; \mathbf{1.7183})$	DM6	Acepta
	1	$GCI_1 = (1{,}0574; \mathbf{1.269}; 1{,}0363; 1{,}0289; 1{,}024; 1{,}2117)$	DM2	Acepta
	2	$GCI_2 = (1{,}0449; 1{,}0862; 1{,}0236; 1{,}045; 1{,}0343; \mathbf{1.1732})$	DM6	Acepta
	3	$GCI_3 = (1{,}0513; \mathbf{1.0677}; 1{,}032; 1{,}0322; 1{,}0282; 1{,}0566)$	DM2	Acepta
	4	$GCI_4 = (1{,}0446; 1{,}0227; 1{,}0253; 1{,}0405; 1{,}0337; \mathbf{1.0471})$	DM6	Acepta
	5	$GCI_5 = (\mathbf{1.048}; 1{,}0179; 1{,}0298; 1{,}034; 1{,}0309; 1{,}0158)$	DM1	Acepta
	6	$GCI_6 = (1{,}0162; 1{,}0145; \mathbf{1.0352}; 1{,}0292; 1{,}0249; 1{,}0183)$	DM3	Acepta
	7	$GCI_7 = (1{,}0197; 1{,}0113; 1{,}0118; \mathbf{1.0244}; 1{,}021; 1{,}022)$	DM4	Acepta
	8	$GCI_8 = (1{,}0172; 1{,}0142; 1{,}0094; 1{,}0083; \mathbf{1.0234}; 1{,}0183)$	DM5	Acepta
	9	$GCI_9 = (1{,}014; 1{,}0163; 1{,}0074; 1{,}0099; 1{,}0079; \mathbf{1.0167})$	DM6	Acepta
	10	$GCI_{10} = (\mathbf{1.0155}; 1{,}0137; 1{,}009; 1{,}008; 1{,}0071; 1{,}0056)$	DM1	Acepta
	11	$GCI_{11} = (1{,}0052; \mathbf{1.0119}; 1{,}0107; 1{,}0066; 1{,}0056; 1{,}0066)$	DM2	Acepta
	12	$GCI_{12} = (1{,}0044; 1{,}0041; 1{,}009; 1{,}0082; 1{,}0064; 1{,}0053)$	Detiene	
Criterio Costo	0	$GCI_0 = (1{,}0347; 1{,}0347; 1{,}4038; 1{,}0056; 1{,}2488; \mathbf{1.6923})$	DM6	Acepta
	1	$GCI_1 = (1{,}0622; 1{,}0622; \mathbf{1.3156}; 1{,}0015; 1{,}1849; 1{,}2039)$	DM3	Acepta
	2	$GCI_2 = (1{,}0418; 1{,}0418; 1{,}0984; 1{,}0026; \mathbf{1.2264}; 1{,}164)$	DM5	Acepta
	3	$GCI_3 = (1{,}0276; 1{,}0276; 1{,}1243; 1{,}0075; 1{,}0734; \mathbf{1.1323})$	DM6	Acepta
	4	$GCI_4 = (1{,}0384; 1{,}0384; \mathbf{1.1037}; 1{,}0035; 1{,}0577; 1{,}0436)$	DM3	Acepta
	5	$GCI_5 = (1{,}0287; 1{,}0287; 1{,}0342; 1{,}0064; \mathbf{1.0708}; 1{,}0336)$	DM5	Acepta
	6	$GCI_6 = (1{,}0218; 1{,}0218; \mathbf{1.0426}; 1{,}0104; 1{,}0237; 1{,}026)$	DM3	Acepta
	7	$GCI_7 = (1{,}0244; 1{,}0244; 1{,}0195; 1{,}0191; \mathbf{1.034}; 1{,}0283)$	DM5	Acepta
	8	$GCI_8 = (\mathbf{1.0164;\ 1.0164}; 1{,}0149; 1{,}0143; 1{,}0076; 1{,}0049)$	DM1;DM2	Acepta
	9	$GCI_9 = (1{,}0073; 1{,}0073; \mathbf{1.0102}; 1{,}0097; 1{,}0044; 1{,}0083)$	DM3	Acepta
	10	$GCI_{10} = (1{,}0059; 1{,}0059; 1{,}0035; \mathbf{1.0113}; 1{,}0055; 1{,}0069)$	DM4	Acepta
	11	$GCI_{11} = (1{,}0047; 1{,}0047; 1{,}0045; 1{,}0038; 1{,}0069; 1{,}0055)$	Detiene	
Criterio experiencia	0	$GCI_0 = (1{,}103; 1{,}0452; 1{,}2742; \mathbf{1.6208}; 1{,}009; 1{,}2967)$	DM4	Acepta
	1	$GCI_1 = (1{,}1478; 1{,}0409; 1{,}2249; 1{,}1839; 1{,}004; \mathbf{1.2301})$	DM6	Acepta
	2	$GCI_2 = (1{,}1193; 1{,}0462; \mathbf{1.2483}; 1{,}1505; 1{,}0066; 1{,}0749)$	DM3	Acepta
	3	$GCI_3 = (1{,}0963; 1{,}0395; 1{,}0802; \mathbf{1.1266}; 1{,}0108; 1{,}0895)$	DM4	Acepta
	4	$GCI_4 = (\mathbf{1.1163}; 1{,}0355; 1{,}0691; 1{,}0417; 1{,}007; 1{,}0724)$	DM1	Acepta
	5	$GCI_5 = (1{,}0383; 1{,}0344; 1{,}0589; 1{,}0541; 1{,}0049; \mathbf{1.0581})$	DM6	Acepta
	6	$GCI_6 = (1{,}031; 1{,}0364; \mathbf{1.0643}; 1{,}0451; 1{,}0062; 1{,}0195)$	DM3	Acepta
	7	$GCI_7 = (1{,}0278; 1{,}0343; 1{,}0245; \mathbf{1.0414}1{,}0115; 1{,}0262)$	DM4	Acepta
	8	$GCI_8 = (1{,}0271; \mathbf{1.0315}; 1{,}0211; 1{,}0106; 1{,}0081; 1{,}0052)$	DM2	Acepta
	9	$GCI_9 = (\mathbf{1.026}; 1{,}0106; 1{,}0193; 1{,}0097; 1{,}0071; 1{,}006)$	DM1	Acepta
	10	$GCI_{10} = (1{,}0088; 1{,}0103; \mathbf{1.0166}; 1{,}0125; 1{,}0057; 1{,}0042)$	DM3	Acepta
	11	$GCI_{11} = (1{,}0075; 1{,}0092; 1{,}0056; \mathbf{1.011}; 1{,}0067; 1{,}0049)$	DM4	Acepta
	12	$GCI_{12} = (1{,}009; 1{,}0088; 1{,}0049; 1{,}0037; 1{,}0058; 1{,}0038)$	Detiene	
Criterio Flota	0	$GCI_0 = (1{,}0163; 1{,}0287; 1{,}0041; \mathbf{1.0287}; 1{,}0041; 1{,}0041)$	DM4	Acepta
	1	$GCI_1 = (1{,}0172; \mathbf{1.0244}; 1{,}0039; 1{,}0097; 1{,}0039; 1{,}0039)$	DM2	Acepta
	2	$GCI_2 = (\mathbf{1.0178}; 1{,}0083; 1{,}0034; 1{,}0075; 1{,}0034; 1{,}0034)$	DM1	Acepta
	3	$GCI_3 = (1{,}006; 1{,}0088; 1{,}0022; 1{,}0081; 1{,}0022; 1{,}0022)$	Detiene	
Criterio mejora del servicio	0	$GCI_0 = (1{,}0451; 1{,}0281; 1{,}0335; 1{,}0179; \mathbf{1.0517}; 1{,}0179)$	DM5	Acepta
	1	$GCI_1 = (\mathbf{1.047}; 1{,}0248; 1{,}034; 1{,}0151; 1{,}0173; 1{,}0151)$	DM1	Acepta
	2	$GCI_2 = (1{,}0158; \mathbf{1.0291;\ 1.0291}; 1{,}0114; 1{,}019; 1{,}0114)$	DM2; DM3	Acepta
	3	$GCI_3 = (1{,}016; 1{,}0076; 1{,}0076; 1{,}0112; \mathbf{1.018}; 1{,}0112)$	DM5	Acepta
	4	$GCI_4 = (\mathbf{1.0172}; 1{,}0071; 1{,}0078; 1{,}0096; 1{,}0061; 1{,}0096)$	DM1	Acepta
	5	$GCI_5 = (1{,}0058; 1{,}0086; 1{,}0068; 1{,}0078; 1{,}007; 1{,}0078)$	Detiene	
Criterio Higiene y Seguridad	0	$GCI_0 = (\mathbf{1.0401}; 1{,}0074; 1{,}0074; 1{,}0074; 1{,}0122; 1{,}0025)$	DM1	Acepta
	1	$GCI_1 = (1{,}0135; 1{,}0048; 1{,}0048; 1{,}0048; \mathbf{1.0159}; 1{,}0013)$	DM5	Acepta
	2	$GCI_2 = (\mathbf{1.0159}; 1{,}0035; 1{,}0035; 1{,}0035; 1{,}0054; 1{,}0007)$	DM1	Acepta
	3	$GCI_3 = (1{,}0054; 1{,}0024; 1{,}0024; 1{,}0024; 1{,}007; 1{,}0004)$	Detiene	
Criterio tratamiento	0	$GCI_0 = (1{,}0159; \mathbf{1.1415}; 1{,}0252; 1{,}0005; 1{,}0904; 1{,}0227)$	DM2	Acepta
	1	$GCI_1 = (1{,}0122; 1{,}0466; 1{,}0166; 1{,}0008; \mathbf{1.0733}; 1{,}0331)$	DM5	Acepta
	2	$GCI_2 = (1{,}013; \mathbf{1.038}; 1{,}0227; 1{,}0002; 1{,}0245; 1{,}0258)$	DM2	Acepta
	3	$GCI_3 = (1{,}011; 1{,}0128; 1{,}0183; 1{,}0004; 1{,}0201; \mathbf{1.0313})$	DM6	Acepta
	4	$GCI_4 = (1{,}0097; 1{,}0164; 1{,}0148; 1{,}0011; \mathbf{1.0165}; 1{,}0106)$	DM5	Acepta
	5	$GCI_5 = (1{,}0096; 1{,}0141; \mathbf{1.0174}; 1{,}0005; 1{,}0056; 1{,}0087)$	DM3	Acepta
	6	$GCI_6 = (1{,}01; \mathbf{1.0118}; 1{,}0059; 1{,}0002; 1{,}0073; 1{,}007)$	DM2	Acepta
	7	$GCI_7 = (1{,}01; 1{,}0051; 1{,}0056; 1{,}0015; 1{,}0069; 1{,}0098)$	Detiene	

Tabla 3. Resultados finales de la estrategia AHP grupal en la situación simulada I

	Modalidad Operativa	Costo	Experiencia	Flete	Mejora del Servicio	Higiene y Seguridad	Tratamiento	Puntaje
Peso	0.303	0.244	0.135	0.114	0.074	0.071	0.062	
Oferente 1	0.517	0.394	0.536	0.421	0.462	0.448	0.532	0.4705
Oferente 2	0.362	0.320	0.301	0.410	0.376	0.419	0.256	0.3478
Oferente 3	0.121	0.286	0.163	0.151	0.162	0.133	0.212	0.1797

En relación a esta cuestión, procesos DRV incorpora un paso fundamental en la fase de estabilización correspondiente a la utilización de alguna herramienta grupal que permita la estructuración del problema y la formación de un lenguaje común. Durante esta actividad el grupo discute, verbaliza y define en forma conjunta los criterios y alternativas. Otra cuestión importante en esta fase, es que la asignación de juicios se realiza en forma individual a los fines de mitigar el efecto de la presión grupal.

Con la modalidad de trabajo propuesta en AHP donde el moderador opera sobre el participante más discordante, se pueden perder instancias de intercambio de opiniones y experiencias entre los tomadores de decisiones en la estructuración del problema. Estos problemas asociados con la necesidad de cumplir con la medida de consenso objetiva pueden afectar la posibilidad de construir conocimiento conjunto.

En relación con la imprecisión o error de medición, la versión grupal de AHP recopila los datos solo una vez. Esta situación genera una dificultad para las operaciones posteriores, porque puede arrastrarse el error si existe. En este sentido, antes de un cambio en la información, se pierde flexibilidad para posibles adaptaciones.

En resumen, la estrategia AHP adoptada detecta la falta de consenso y ayuda al grupo a alcanzar un grado predefinido de consenso, al tiempo que reduce los niveles de incertidumbre. Se observa una mejora continua de la medida de consenso en las iteraciones presentadas en el ejemplo al aumentar el número de rondas. Aun así, la estrategia puede incorporar mejoras que consideren los efectos de la presión de grupo y arbitrar medios para trabajar en el error de medición.

4. Conclusiones

Ha sido posible comparar dos métodos grupales considerando sus respuestas en la búsqueda del consenso y el tratamiento que hacen sobre las formas de ignorancia. Ambos métodos tienen mecanismos para tratar ambos factores y han facilitado la decisión final en el caso de aplicación referido a la gestión de residuos patógenos .

En el caso de procesos DRV en particular se resaltan los recaudos del método en la etapa de estructuración del problema, los cuales se orientan a la formación de un lenguaje común. Es más, las actividades de estructuración acompañadas

Tabla 4. Índice de consenso grupal GCI y la elección del tomador de decisiones más discordante para cada subproblema en la situación II

Sub-problema	Iteración	Índice de consenso grupal (GCI)	Decisor más discordante (DM_P)	Elección
Peso del criterio	0	$GCI_0 = (1{,}0596; 1{,}0090; 1{,}0221; 1{,}0163; 1{,}0012; \mathbf{1.0744})$	DM6	Rechaza
	1	$GCI_1 = (\mathbf{1.0596}; 1{,}0090; 1{,}0221; 1{,}0163; 1{,}0012; 1{,}0744)$	DM1	Acepta
	2	$GCI_2 = (1{,}0192; 1{,}0103; 1{,}0221; \mathbf{1.0227}; 1{,}0024; 1{,}0723)$	DM4	Acepta
	3	$GCI_3 = (\mathbf{1.0221}; 1{,}0100; 1{,}0200; 1{,}0062; 1{,}0027; 1{,}0687)$	DM1	Acepta
	4	$GCI_4 = (1{,}0064; 1{,}0103; \mathbf{1.0194}; 1{,}0085; 1{,}0031; 1{,}0659)$	DM3	Acepta
	5	$GCI_5 = (1{,}0088; \mathbf{1.0126}; 1{,}0054; 1{,}0081; 1{,}003; 1{,}0629)$	DM2	Rechaza
Criterio Modalidad Operativa	0	$GCI_0 = (1{,}0458; 1{,}3479; 1{,}0212; 1{,}0543; 1{,}037; \mathbf{1.7183})$	DM6	Rechaza
	1	$GCI_1 = (1{,}0458; \mathbf{1.3479}; 1{,}0212; 1{,}0543; 1{,}037; 1{,}7183)$	DM2	Acepta
	2	$GCI_2 = (1{,}0385; \mathbf{1.1098}; 1{,}0133; 1{,}079; 1{,}0545; 1{,}6205)$	DM2	Acepta
	3	$GCI_3 = (1{,}0362; 1{,}0364; 1{,}0108; \mathbf{1.0958}; 1{,}067; 1{,}5681)$	DM4	Acepta
	4	$GCI_4 = (1{,}0359; 1{,}047; 1{,}0098; 1{,}0319; \mathbf{1.0799}; 1{,}5218)$	DM5	Acepta
	5	$GCI_5 = (1{,}033; \mathbf{1.0571}; 1{,}0086; 1{,}0402; 1{,}0266; 1{,}4893)$	DM2	Acepta
	6	$GCI_6 = (1{,}034; 1{,}0192; 1{,}0095; \mathbf{1.0486}; 1{,}0332; 1{,}4574)$	DM4	Acepta
	7	$GCI_7 = (1{,}0357; 1{,}0246; 1{,}011; 1{,}0164; \mathbf{1.0399}; 1{,}4292)$	DM5	Acepta
	8	$GCI_8 = (\mathbf{1.036}; 1{,}0299; 1{,}0122; 1{,}0207; 1{,}0134; 1{,}4082)$	DM1	Acepta
	9	$GCI_9 = (1{,}0121; \mathbf{1.0321}; 1{,}0149; 1{,}0225; 1{,}014; 1{,}393)$	DM2	Acepta
	10	$GCI_{10} = (1{,}0137; 1{,}0108; 1{,}0175; \mathbf{1.0273}; 1{,}0177; 1{,}3718)$	DM4	Acepta
	11	$GCI_{11} = (1{,}0156; 1{,}0139; 1{,}0202; 1{,}0092; \mathbf{1.0215}; 1{,}353)$	DM5	Acepta
	12	$GCI_{12} = (1{,}0172; 1{,}0169; \mathbf{1.0226}; 1{,}0117; 1{,}0073; 1{,}3379)$	DM3	Acepta
	13	$GCI_{13} = (\mathbf{1.0201}; 1{,}0195; 1{,}0076; 1{,}0139; 1{,}0089; 1{,}322)$	DM1	Acepta
	14	$GCI_{14} = (1{,}0079; \mathbf{1.0239}; 1{,}0038; 1{,}0177; 1{,}0116; 1{,}322)$	DM2	Acepta
	15	$GCI_{15} = (1{,}0141; 1{,}0128; 1{,}0088; 1{,}0092; 1{,}006; 1{,}322)$	Detiene	
Criterio Costo	0	$GCI_0 = (1{,}0347; 1{,}0347; 1{,}4038; 1{,}0056; 1{,}2488; \mathbf{1.6923})$	DM6	Rechaza
	1	$GCI_1 = (1{,}0347; 1{,}0347; \mathbf{1.4038}; 1{,}0056; 1{,}2488; 1{,}6923)$	DM3	Acepta
	2	$GCI_2 = (1{,}0187; 1{,}0187; 1{,}1234; 1{,}0131; \mathbf{1.3051}; 1{,}5895)$	DM5	Acepta
	3	$GCI_3 = (1{,}0089; 1{,}0089; \mathbf{1.1576}; 1{,}025; 1{,}0973; 1{,}5067)$	DM3	Acepta
	4	$GCI_4 = (1{,}0039; 1{,}0039; 1{,}0512; 1{,}0355; \mathbf{1.1189}; 1{,}452)$	DM5	Acepta
	5	$GCI_5 = (1{,}0014; 1{,}0014; \mathbf{1.0649}; 1{,}0471; 1{,}0393; 1{,}4069)$	DM3	Acepta
	6	$GCI_6 = (1{,}0004; 1{,}0004; 1{,}0217; \mathbf{1.0565}; 1{,}0481; 1{,}3756)$	DM4	Acepta
	7	$GCI_7 = (1{,}0004; 1{,}0004; 1{,}0277; 1{,}019; \mathbf{1.0573}; 1{,}3476)$	DM5	Acepta
	8	$GCI_8 = (1{,}0012; 1{,}0012; \mathbf{1.0347}; 1{,}0249; 1{,}0192; 1{,}3208)$	DM3	Acepta
	9	$GCI_9 = (1{,}0022; 1{,}0022; 1{,}0117; \mathbf{1.0299}; 1{,}0238; 1{,}3009)$	DM4	Acepta
	10	$GCI_{10} = (1{,}0037; 1{,}0037; 1{,}015; 1{,}0101; \mathbf{1.0285}; 1{,}283)$	DM5	Acepta
	11	$GCI_{11} = (1{,}0055; 1{,}0055; \mathbf{1.0186}; 1{,}0131; 1{,}0096; 1{,}2662)$	DM3	Acepta
	12	$GCI_{12} = (1{,}0073; 1{,}0073; 1{,}0063; \mathbf{1.0159}; 1{,}012; 1{,}2531)$	DM4	Acepta
	13	$GCI_{13} = (1{,}0091; 1{,}0091; 1{,}0081; 1{,}0054; \mathbf{1.0144}; 1{,}2531)$	DM5	Acepta
	14	$GCI_{14} = (\mathbf{1.0111; 1.0111}; 1{,}01; 1{,}0069; 1{,}0049; 1{,}2304)$	DM1, DM2	Acepta
	15	$GCI_{15} = (1{,}0049; 1{,}0049; 1{,}0137; 1{,}0102; 1{,}0076; 1{,}2121)$	Detiene	
Criterio Experiencia	0	$GCI_0 = (1{,}103; 1{,}0452; 1{,}2742; \mathbf{1.6208}; 1{,}009; 1{,}2967)$	DM4	Rechaza
	1	$GCI_1 = (1{,}103; 1{,}0452; 1{,}2742; 1{,}6208; 1{,}009; \mathbf{1.2967})$	DM6	Acepta
	2	$GCI_2 = (1{,}0773; 1{,}0563; \mathbf{1.3097}; 1{,}5371; 1{,}0173; 1{,}0953)$	DM3	Acepta
	3	$GCI_3 = (1{,}0566; 1{,}0548; 1{,}0983; 1{,}4707; 1{,}0269; \mathbf{1.1163})$	DM6	Acepta
	4	$GCI_4 = (1{,}044; 1{,}0647; \mathbf{1.1128}; 1{,}4247; 1{,}0361; 1{,}0385)$	DM3	Acepta
	5	$GCI_5 = (1{,}0343; \mathbf{1.0678}; 1{,}0373; 1{,}3887; 1{,}0456; 1{,}0477)$	DM2	Acepta
	6	$GCI_6 = (1{,}029; 1{,}0227; 1{,}0402; 1{,}3646; 1{,}051; \mathbf{1.0555})$	DM6	Acepta
	7	$GCI_7 = (1{,}0228; 1{,}0278; 1{,}0473; 1{,}3371; \mathbf{1.0599}; 1{,}0186)$	DM5	Acepta
	8	$GCI_8 = (1{,}0083; 1{,}0215; \mathbf{1.0411}; 1{,}3058; 1{,}0061; 1{,}0112)$	DM3	Acepta
	9	$GCI_9 = (1{,}0126; \mathbf{1.0371}; 1{,}0187; 1{,}2883; 1{,}0256; 1{,}0302)$	DM2	Acepta
	10	$GCI_{10} = (1{,}0099; 1{,}0125; 1{,}0217; 1{,}2709; 1{,}0298; \mathbf{1.0355})$	DM6	Acepta
	11	$GCI_{11} = (1{,}0072; 1{,}0159; 1{,}0263; 1{,}2526; \mathbf{1.0354}; 1{,}012)$	DM5	Acepta
	12	$GCI_{12} = (1{,}0049; 1{,}0195; \mathbf{1.0315}; 1{,}2355; 1{,}012; 1{,}0156)$	DM3	Acepta
	13	$GCI_{13} = (1{,}003; \mathbf{1.023}; 1{,}0106; 1{,}2203; 1{,}0153; 1{,}0193)$	DM2	Acepta
	14	$GCI_{14} = (1{,}0021; 1{,}0078; 1{,}0129; 1{,}2077; 1{,}0183; 1{,}0228)$	DM6	Acepta
	15	$GCI_{15} = (1{,}0012; 1{,}0101; 1{,}0159; 1{,}1952; 1{,}0218; 1{,}0077)$	Detiene	
Criterio Flota	0	$GCI_0 = (1{,}0163; \mathbf{1.0287}; 1{,}0041; \mathbf{1.0287}; 1{,}0041; 1{,}0041)$	DM2,DM4	Rechaza. Acepta
	1	$GCI_1 = (\mathbf{1.0172}; 1{,}0244; 1{,}0039; 1{,}0097; 1{,}0039; 1{,}0039)$	DM1	Acepta
	2	$GCI_2 = (1{,}0058; 1{,}025; 1{,}0027; \mathbf{1.0105}; 1{,}0027; 1{,}0027)$	DM4	Acepta
	3	$GCI_3 = (1{,}0064; 1{,}0228; 1{,}0028; 1{,}0035; 1{,}0028; 1{,}0028)$	Detiene	
Criterio Mejora del Servicio	0	$GCI_0 = (1{,}0451; 1{,}0281; 1{,}0335; 1{,}0179; \mathbf{1.0517}; 1{,}0179$	DM5	Rechaza
	1	$GCI_1 = (\mathbf{1.0451}; 1{,}0281; 1{,}0335; 1{,}0179; 1{,}0517; 1{,}0179)$	DM1	Acepta
	2	$GCI_2 = (1{,}0152; \mathbf{1.0326}; 1{,}0284; 1{,}0144; 1{,}0536; 1{,}0144)$	DM2	Acepta
	3	$GCI_3 = (1{,}0085; 1{,}0104; \mathbf{1.0225}; 1{,}013; 1{,}05; 1{,}013)$	DM3	Acepta
	4	$GCI_4 = (1{,}0064; 1{,}0085; 1{,}0064; \mathbf{1.0136}; 1{,}0491; \mathbf{1.0136})$	DM4; DM6	Acepta
	5	$GCI_5 = (1{,}0033; 1{,}0084; 1{,}0077; 1{,}0048; 1{,}0419; 1{,}0048)$	Detiene	
Criterio Higiene y Seguridad	0	$GCI_0 = (\mathbf{1.0401}; 1{,}0074; 1{,}0074; 1{,}0074; 1{,}0122; 1{,}0025)$	DM1	Rechaza
	1	$GCI_1 = (1{,}0401; 1{,}0074; 1{,}0074; 1{,}0074; \mathbf{1.0122}; 1{,}0025)$	DM5	Acepta
	2	$GCI_2 = (1{,}0437; 1{,}006; 1{,}006; 1{,}006; 1{,}0041; 1{,}0017)$	Detiene	
Criterio Tratamiento	0	$GCI_0 = (1{,}0159; \mathbf{1.1415}; 1{,}0252; 1{,}0005; 1{,}0904; 1{,}0227)$	DM2	Rechaza
	1	$GCI_1 = (1{,}0159; 1{,}1415; 1{,}0252; 1{,}0005; \mathbf{1.0904}; 1{,}0227)$	DM5	Acepta
	2	$GCI_2 = (1{,}0185; 1{,}1235; \mathbf{1.0335}; 1{,}0012; 1{,}0301; 1{,}0162)$	DM3	Acepta
	3	$GCI_3 = (1{,}021; 1{,}1128; 1{,}0113; 1{,}0023; \mathbf{1.0356}; 1{,}0126)$	DM5	Acepta
	4	$GCI_4 = (\mathbf{1.0238}; 1{,}1027; 1{,}0148; 1{,}0039; 1{,}012; 1{,}0096)$	DM1	Acepta
	5	$GCI_5 = (1{,}008; 1{,}0954; \mathbf{1.0171}; 1{,}0055; 1{,}0139; 1{,}0075)$	DM3	Acepta
	6	$GCI_6 = (1{,}0096; 1{,}0887; 1{,}0058; 1{,}0071; \mathbf{1.0166}; 1{,}0058)$	DM5	Acepta
	7	$GCI_7 = (\mathbf{1.0113}; 1{,}0824; 1{,}0075; 1{,}0089; 1{,}0056; 1{,}0043)$	DM1	Rechaza
	8	$GCI_8 = (1{,}0113; 1{,}0824; 1{,}0075; 1{,}0089; 1{,}0056; 1{,}0043)$	Detiene	

Tabla 5. Resultados finales de la estrategia AHP grupal en la situación simulada II

	Modalidad Operativa	Costo	Experiencia	Flete	Mejora del Servicio	Higiene y Seguridad	Tratamiento	Puntaje
Pesos	0.302	0.228	0.131	0.117	0.079	0.075	0.068	
Oferente 1	0.671	0.287	0.666	0.321	0.446	0.460	0.473	0.4947
Oferente 2	0.254	0.327	0.239	0.370	0.403	0.413	0.281	0.3077
Oferente 3	0.076	0.387	0.094	0.140	0.150	0.127	0.246	0.1778

de formas de recolección independiente y la presentación de la información con medidas indirectas obstaculizan la adaptación del grupo al pensamiento dominante y así se reduce la presión de los pares. Adicionalmente, es posible trabajar con herramientas potentes en la fase de estabilización (IVR y normalidad de los datos) que permiten disminuir los efectos de las dificultades sobre la información no relacionados a la imprecisión y la incertidumbre.
En el caso del método grupal de AHP en la versión de Dong y Saaty, hay una etapa de estructuración de problemas a través del diagrama de árbol, aún así en la instancia grupal no se indica en qué forma se llevan adelante los intercambios en esta actividad de estructuración. En cuanto a la presión grupal, la no indicación de recolección de utilidades de tipo subjetivo de forma individual e independiente acompañada de la sugerencia del moderador sobre el participante más discordante pueden acelerar la búsqueda de una solución de cierre que favorezca la opinión de algunos, con la pérdida de instancias de intercambio de las restantes opiniones. Adicionalmente, el gran número de iteraciones que deben efectuarse puede llevar a cansancio de los participantes y del analista en el procesamiento. En cuanto a la imprecisión o error de medición, la versión grupal de AHP recopila los datos solo una vez lo que en las operaciones posteriores puede arrastrar el error si existe, y en relación a la incertidumbre, esta se ve reducida.
En cuanto a las limitaciones de este trabajo, se encuentra el hecho de que los datos se recolectaron a partir de un método y debieron ser adaptados al otro para mostrar la comparación y las formas de trabajo. Debido a ser el caso de aplicación real por cuestiones de agenda del grupo de trabajo no fue posible aplicar ambos métodos en forma completa.
Por último, quedan líneas abiertas de investigación para trabajar con la comparación de otros métodos grupales. Adicionalmente, pueden analizarse qué otras métricas pueden ser pertinentes para la comparación de métodos, como por ejemplo la reversión de rangos, el análisis de sensibilidad, por sólo mencionar algunas.

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National Health Systems and doubling time of number of deaths by COVID-19 Coronavirus

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Abstract. COVID-19 has placed stress on all national health systems worldwide. Recent studies of the disease have evaluated different variables, quarantine models, mitigation efforts, damage to the mental health, mortality of the population with chronic diseases, diagnosis of the disease, use of masks and social distancing, or mortality regarding different age groups. This study focuses on the capacity of the four National Health System recognized by the WHO. These systems are: (1) The Beveridge model, (2) the Bismarck model, (3) the National Health insurance model, and (4) the "Out of pocket" model. The capacity to respond to the pandemic is analyzed through the days where the mortality doubles by comparing the medians of the doubling mortality variables using the Mood's median test method. The results obtained show similar medians between the study groups. The COVID-19 pandemic saturates health systems regardless of their management structures and the result measured with the variable 'days with double the mortality' is similar among the 4 national health systems.

Keywords: COVID-19, coronavirus, National Health Systems, death rate, non-parametric test.

1 Introduction

Over the last 10 months COVID-19 has spread from China to the rest of the world. National health systems have implemented different strategies to control the disease [1–10] to reduce the rate of infection and mortality. Different authorities have identified different factors associated with the distinctive dynamic system of the disease: climatic factors [11–15], pre-existing disease conditions [16], mental illnesses [17–23], prediction models [24, 25], social distancing [26], and mask, among others [27–31].

Currently, the pandemic has more than 20 million confirmed cases worldwide with 750,000 deaths. America is the continent with the most active cases; Europe is on alert

for outbreaks or a "second wave" of infections. There are currently several studies in the search for a cure that are in the phase of clinical trials in humans [32].

Regarding health systems, there are four national health systems: (1) The Beveridge model, this model is financed by direct taxes, where the person being treated does not pay for care. Also in this model, most of the clinics and hospitals are owned by the government and most of the employees are government employees. This system is implemented in countries such as Great Britain and Spain. (2) The Bismarck model, is financed by private health insurance. This system is jointly financed by employers as employees through payroll deduction, medical care is paid for and reimbursed by insurance, and health centers and doctors are generally private. This system is applied in Germany, France, and Japan. (3) The National Health insurance model, is financed through payroll and tax deductions. These payments are turned over to the national health insurance program, which is administered by the government. The health service is provided by private hospitals and doctors. Some countries only allow the provision of health services to non-profit Private Foundations to achieve cost containment. This system is applied in countries like Canada and South Korea, among others. The last health system corresponds to the so-called (4) “out-of-pocket” system, which is based on the lack of universal health coverage, the patient must pay for their health expenses. In this system, those with the highest income will be able to take care of themselves and the poor will continue to be ill or die. This system is applied in countries within Latin America, Africa, Eastern Europe, and Asia [33–35]. Each system has its characteristics and different approaches and they are heterogeneously distributed in different countries.

The study evaluated the relationship between National Health Systems and the doubling time of the COVID-19 death by country, to evaluate the performance of the different health systems in their response to the pandemic.

2 The Four National Health Systems

The Beveridge model was founded in 1948 by William Beveridge. In this system, health coverage is universal, the health care system is available to all citizens without direct payment, and it is financed by the government through taxes. Most hospitals and clinics are owned by the government and the officials are public employees. The state pays the health care, managing to regulate prices, and define the quality and costs of health care. Private clinics are also financed by the state, which defines health care and the value of each health benefit. The greatest weakness of the system is the long waiting times for medical attention. This system is known globally as the National Health Service (NHS).

The Bismarck model was established by the Prussian Chancellor Otto von Bismarck during the German unification in the 19th century, this system uses an insurance system, called sickness funds. These insurances are jointly financed between employers and employees under payroll discounts. In this case, all members contribute to a defined insurance fund and this provides defined benefits. Private insurance companies must be non-profit; They exist for self-employed citizens and for those who wish to receive

elective services that are not covered by sickness funds. This model has a multi-payer system, where each country has a different number of insurers to choose from. This system has universal coverage and very strict regulations with the sole objective of reaching the entire population and being a non-profit entity.

The National Health Insurance (NHI) model is based on the existence of a universal and unique health insurance system defined in a geographic area and financed by the Government through different sources such as taxes and social security contributions. The NHI model maintains strict independence between the universal insurance system provided by the Government and the medical providers made up by foundations or private companies. The benefits are regulated by a general benefit contract. This contract allows (1) to limit an increase of providers, (2) to share the risk of diseases among the entire population, (3) to ensure the universal availability for all citizens, (4) a general regulation for all providers, and (5) ensures adequate and timely provision of medical services. The fundamental difference between the NHS and the NHI is the separation between universal government insurance and the provision of medical services. In the NHI system, the Government negotiates prices and benefits with private companies and foundations; the government delegates all medical provision services to independent entities. This health care system has been adopted by the governments of Canada, Taiwan, and South Korea. Finally, the model based on universality does not require advertising expenses, reduces the cost of uncertainty by sharing risk, has no financial incentives for denial of service, does not cause bankruptcies in the population, and generates savings for the population due to its public nature.

The Out of Pocket model corresponds to health systems in very poor and disorganized nations where the provision of medical services is not universal and corresponds to an economic transaction between the citizen and private medical service. Large areas of China, India, and rural Africa do not have adequate medical services for their population. About 40 industrialized countries maintain robust national health systems. The United States has a health system where each citizen based on their social and economic position can be classified in one of the 4 national health systems.

3 Methodology

We reviewed the literature regarding the mortality associated with the COVID-19 disease in different countries; however, the analysis was limited to 57 nations representing 70% of the global population. The characteristics of these nations are described in Table 1, with an analysis of mortality up to the 1st of July, 2020. Subsequently, the countries were classified into one of the four national health system models. The information for classification was obtained from the WHO, and the reports associated with each country. Subsequently, the statistical analysis of the comparison of medians of the doubling mortality time variable (Ec. 1) was performed with the Mood technique; using different cut-off dates to see the impact of the pandemic on each health system.

$$Dt = Period / Log^2 (D1 / D0) \quad (1)$$

Where *D0* is the first day with accumulated deaths equal to 10 and *D1* is day i with n accumulated deaths.

Table 1. Doubling time of number of deaths by country

Country	Population at 2020 estimated (thousand)	Start Period	Total death as of D0	Total death as D1	Period length P (day)	Growth ratio: R	Doubling time (day) (90 d)	Doubling time (day) (75 d)	Doubling time (day) (60 d)	Healthcare System
USA	331,003	5-Mar	11	106,181	90	9652.8	6.80	5.77	4.77	Out-of-Pocket
Brazil	212,559	21-Mar	11	47,748	90	4340.7	7.45	6.50	5.62	Bismarck
UK	67,886	13-Mar	10	41,128	90	4112.8	7.50	6.33	5.15	Beveridge
Italy	60,462	26-Feb	11	32,877	90	2988.8	7.80	6.56	5.34	Beveridge
France	65,274	8-Mar	10	29,111	90	2911.1	7.82	6.54	5.29	Bismarck
Mexico	128,933	28-Mar	12	25,060	90	2088.3	8.16	7.27	6.38	Out-of-Pocket
India	1,380,004	26-Mar	13	14,476	90	1113.5	8.89	8.18	7.25	Out-of-Pocket
Spain	46,755	10-Mar	28	27,136	90	969.1	9.07	7.50	6.07	Beveridge
Russia	145,934	31-Mar	10	9,073	90	907.3	9.16	7.97	6.84	Beveridge
Canada	37,742	20-Mar	10	8,254	90	825.4	9.29	7.87	6.53	National Health
Peru	32,972	28-mar	11	8761	90	796.5	9.34	8.27	7.12	Out-of-Pocket
Germany	83,784	16-Mar	12	8,787	90	732.3	9.46	7.92	6.42	Bismarck
Belgium	11,590	19-Mar	14	9,692	90	692.3	9.54	7.97	6.42	Bismarck
Iran	83,993	25-Feb	12	7,417	90	618.1	9.71	8.24	6.77	Bismarck
Netherlands	17,135	15-Mar	12	6,053	90	504.4	10.02	8.39	6.77	Bismarck
Sweden	10,099	19-Mar	10	4,939	90	493.9	10.06	8.54	7.04	Beveridge
Chile	19,116	1-Apr	12	5,575	90	464.6	10.16	9.24	9.41	Bismarck
Pakistan	220,892	29-Mar	11	4,035	90	366.8	10.56	9.61	8.77	Out-of-Pocket
South Africa	59,309	6-Apr	11	2,657	86	241.5	10.86	10.16	9.57	Beveridge
Ecuador	17,643	23-Mar	14	4,199	90	299.9	10.94	9.40	7.78	Bismarck
Colombia	50,883	30-Mar	10	2,939	90	293.9	10.98	10.31	9.43	Bismarck
China	1,439,324	22-Jan	17	4,636	90	272.7	11.12	9.85	7.91	Out-of-Pocket
Turkey	84,339	22-Mar	21	4,905	90	233.6	11.44	9.63	7.84	Beveridge
Egypt	102,334	23-Mar	10	2,106	90	210.6	11.66	10.92	9.80	Out-of-Pocket
Bangladesh	164,689	7-Apr	12	1,847	85	153.9	11.70	10.88	9.87	Out-of-Pocket
Saudi Arabia	34,814	1-Apr	10	1,599	90	159.9	12.29	11.36	10.74	Beveridge

Switzer-land	8,655	15-Mar	11	1,676	90	152.4	12.41	10.37	8.39	Bismarck
Romania	19,238	25-Mar	11	1,523	90	138.5	12.65	10.85	8.91	Bismarck
Poland	37,847	25-Mar	10	1359	90	135.9	12.70	10.94	9.04	Bismarck
Portugal	10,197	22-Mar	12	1,527	90	127.3	12.87	10.84	8.93	Beveridge
Indonesia	273,524	20-Mar	19	2,276	90	119.8	13.04	11.62	10.05	Out-of-Pocket
Ukraine	43,734	31-Mar	11	1,129	90	102.6	13.47	11.86	10.03	Out-of-Pocket
Ireland	4,938	27-Mar	19	1,726	90	90.8	13.83	11.58	9.37	Beveridge
Argentina	45,196	27-Mar	12	1,085	90	90.4	13.85	12.71	11.36	Bismarck
Philippines	109,581	16-Mar	12	1,074	90	89.5	13.88	11.91	9.93	Out-of-Pocket
Algeria	43,851	21-Mar	10	811	90	81.1	14.19	12.38	10.33	Out-of-Pocket
Japan	126,476	11-Mar	12	916	90	76.3	14.39	12.27	10.57	Bismarck
Dominican Republic	10,848	26-Mar	10	675	90	67.5	14.81	13.04	10.87	Out-of-Pocket
Iraq	40,223	18-Mar	11	652	90	59.3	15.28	17.77	17.34	Out-of-Pocket
Hungary	9,660	25-Mar	10	573	90	57.3	15.41	13.02	10.71	Bismarck
Moldova	4,034	5-Apr	12	545	87	45.4	15.80	14.40	12.79	Out-of-Pocket
Denmark	5,792	22-Mar	13	600	90	46.2	16.28	13.68	11.08	Beveridge
Austria	9,006	23-Mar	16	688	90	43.0	16.59	13.91	11.31	Bismarck
Panama	4,315	28-mar	14	564	90	40.3	16.88	15.36	13.38	Out-of-Pocket
Czechia	10,709	29-mar	11	345	90	31.4	18.10	15.30	12.37	Bismarck
Israel	8,656	28-Mar	10	309	90	30.9	18.18	15.30	12.47	Bismarck
Macedonia	2,083	2-Apr	10	302	90	30.2	18.31	17.56	16.07	Out-of-Pocket
Finland	5,541	30-Mar	11	328	90	29.8	18.37	15.35	12.42	Beveridge
Serbia	8,737	29-Mar	10	265	90	26.5	19.04	16.11	13.09	Out-of-Pocket
Norway	5,421	25-Mar	10	248	90	24.8	19.43	16.40	13.17	Beveridge
S. Korea	51,269	26-Feb	11	269	90	24.5	19.51	16.52	13.45	National Health
Morocco	36,911	27-Mar	10	216	90	21.6	20.30	17.08	13.88	Out-of-Pocket
Greece	10,423	22-Mar	13	189	90	14.5	23.31	19.82	16.33	Bismarck
Puerto Rico	2,861	2-Apr	11	153	90	13.9	23.70	20.05	16.54	Out-of-Pocket
Malaysia	32,366	23-Mar	10	121	90	12.1	25.02	21.21	17.09	Bismarck
Slovenia	2,079	30-Mar	11	111	90	10.1	26.99	22.67	18.21	Bismarck
Australia	25,500	26-Mar	11	102	90	9.3	28.01	23.34	18.67	National Health

3.1 Results

The analysis dates correspond to 60, 75, and 90 days post day 1 with a cumulative number of 10 deaths. Box charts in figure 1 show similar medians for each national health system.

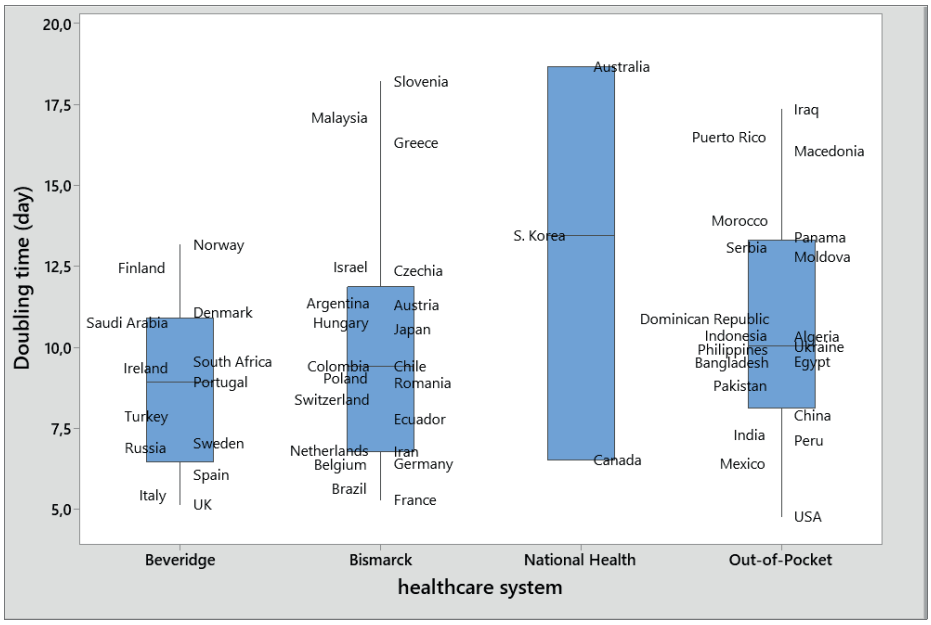

Fig. 1. Box Graph of day 90

To determine whether or not there are significant differences in the information, the Mood median test was performed for each date of the study. Based on a MOOD non-parametric test, the distributions of these four groups were not significantly different when using a significance value of 0.05 (p-value = 0.361 for 60 days, p-value = 0.361 for 75 days, p-value = 0.117 for 90 days). As seen in Table 1, the P-value for each date shows the absence of statistical differences between the different health systems regarding their capacity to respond to the COVID-19 pandemic.

4 Conclusions

The COVID-19 pandemic has been studied from numerous aspects: climatic factors, pre-existing disease conditions, mental illnesses, quarantine models, social distancing, age, use of mask among others.

This study evaluated the relationship between National Health Systems and the doubling time of the COVID-19 death by country to evaluate their performance during the pandemic.

The 4 national health insurance models compared in this study were: (1) The Beveridge model, (2) the Bismarck model, (3) the National Health Insurance model, and (4) the "Out of Pocket" model. The classification of each model in different countries has been studied by international organizations such as the WHO.

The P-values of the different time periods (60, 75, and 90 days) show no significant difference in the doubling mortality time between the different health systems.
Finally, the study establishes no difference in the performance of the different health systems during the COVID-19 pandemic. However, multidimensional modeling must be carried out to know the causes of the doubling mortality time.

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Modelación del proceso de programación de pacientes en listas de espera en un hospital público de Chile

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Abstract. Se aborda la modelación del proceso de selección y priorización de pacientes en listas de espera quirúrgicas electivas en un hospital público en Chile en base a información histórica con fines de elaborar un modelo de simulación que permita analizar diferentes políticas de configuración y operación del sistema de pabellones quirúrgicos y listas de espera. Se cuenta con datos de un año con aproximadamente 15.000 intervenciones en más de 600 patologías, 8.000 pacientes en la lista de espera inicial, 15 pabellones, 150 cirujanos, cuatro periodos horarios diarios y consideración de fines de semana. Con ellos se modelan procesos clave del sistema de pabellones quirúrgicos. Se utiliza conocimiento experto sobre los procesos de planificación y ejecución de intervenciones quirúrgicas que representan la operación del sistema. Se modela la priorización de pacientes a través de un ranking de selección en cada clúster, representado como una distribución de posición relativa en la lista de espera.
Se usan múltiples indicadores para validar la representatividad del modelo de simulación elaborado, concluyéndose que la modelación del proceso de priorización de pacientes refleja eficientemente el desempeño del sistema, constituyéndose en una herramienta útil y fácil de implementar en el contexto de la simulación del sistema de pabellones quirúrgicos.

Keywords: Pabellones Quirúrgicos, Gestión hospitalaria, Listas de espera quirúrgicas, Priorización de Cirugías.

1 Introducción

Proporcionar una buena calidad de atención es un objetivo primordial, de hecho, una prioridad y un deber de las instituciones de salud en todo el mundo. (Barbagallo et al., 2015). Sin embargo, los recursos estructurales del Sistema Nacional de Salud son limitados y no se pueden intervenir quirúrgicamente a todos los pacientes oportunamente. En la espera quirúrgica los pacientes soportan dolor creciente, limitaciones funcionales y pérdida de calidad de vida relacionada con la salud, llegando incluso a la muerte del paciente a la falta de atención (Desmeules et al., 2012). Además de la poca disponibilidad de recursos escasos de los hospitales (Durán et al., 2017) se presentan problemas de gestión de los mismos, que afectan el rendimiento general de cada pabellón (Garbey

et al., 2017). Existe evidencia que demuestra la optimización de utilización de pabellones por entre un 10 y un 15% respecto a métodos de programación manuales (Durán et al., 2017).

Las listas de espera y los tiempos de espera son un motivo de preocupación en el mundo (Rojas et al., 2017). Los autores además se refieren a que "en las últimas dos décadas se han desarrollado múltiples estrategias enfocadas a reducir el tamaño o a disminuir el tiempo de espera, o simplemente, orientadas a racionalizar la lista". Tradicionalmente el tiempo de espera ha sido el criterio más utilizado para el manejo de dichas listas, pero se discute cada vez más su pertinencia, bajo el argumento de que no siempre el paciente que más tiempo lleva esperando es el que más necesita la intervención (Escobar et al., 2005).

Por otro lado, el movimiento quirúrgico "es considerado una variable que interfiere en los indicadores de calidad y productividad de las instituciones hospitalarias. Se constituye en parámetros de evaluación de la productividad en la sala de cirugía, o sea, tasa de ocupación, tiempo de permanencia, recuperación anestésica, intervalo de tiempo entre cirugías, tasa de retraso y suspensión de cirugía" (Abeldaño & Coca, 2016).

En ese contexto, se modela los procesos de priorización de pacientes en lista de espera en el Hospital Público Puerto Montt, con fines de elaborar un modelo de simulación que permita analizar diferentes estrategias de configuración y operación del sistema de pabellones quirúrgicos. Se utilizan datos de operación del año 2017 con 15.000 intervenciones en más de 600 patologías, 8.000 pacientes en la lista de espera inicial, 15 pabellones, 150 cirujanos, cuatro periodos horarios diarios y consideración de fines de semana. Los datos incluyen tipo de intervención realizada, tipo y fecha de ingreso al sistema, equipo clínico y pabellón asignado, tiempos de ejecución de cada etapa del proceso en el pabellón quirúrgico. No se incluye información clínica detallada del paciente.

2 Modelo del Sistema de Priorización

A continuación se describe los aspectos más relevantes del sistema y el modelo construido:

Caracterización de patologías. Se consideran 633 patologías diferentes, en 10 especialidades médicas y 35 subespecialidades. Por facilidad se realizó un análisis de conglomerado jerárquico resultando en 47 grupos según las variables determinantes.

Ingreso de pacientes. Existe 3 fuentes de pacientes para los pabellones quirúrgicos: Listas de Espera para intervenciones electivas, Urgencias desde el servicio de atención regular y Otras entradas (pacientes del sistema de Garantías Explícitas de Salud GES). A su vez, los pacientes en Lista de Espera provienen de un listado histórico más los ingresos que ocurren diariamente en las diferentes patologías. Cada uno de estos flujos ocurre a diferentes tasas, diferenciados por patología. Se utiliza tablas de frecuencia para modelar las tasas de ingreso.

Resolutividad quirúrgica y no quirúrgica. Aproximadamente un 75% de los pacientes en lista de espera al comienzo del año constituyen pacientes efectivos, en tanto el 25% restante recibe una resolución no quirúrgica, descargándose del sistema.

Tiempos de proceso para intervenciones quirúrgicas. Se consideran 5 etapas en el proceso quirúrgico: preparación del paciente, aplicación de anestesia, intervención quirúrgica, recuperación en pabellón, descarga a sala de recuperación. Para los 47 clúster definidos se establecen las distribuciones correspondientes a sus duraciones y sus parámetros.

Selección de patologías. Los ingresos de urgencia y otros son asignados inmediatamente para intervención teniendo prioridad por sobre los pacientes en lista de espera. La capacidad remanente de los pabellones se asigna a patologías de acuerdo a la frecuencia de ocurrencia correspondiente al clúster respectivo.

Priorización de pacientes. Se establece una función de ranking relativo histórico para la selección de pacientes en lista de espera. Éste se calcula para un paciente como la posición porcentual dentro de la lista correspondiente al momento de ser seleccionado. La forma general de esta función es de tipo U, mostrando una tendencia a seleccionar con mayor probabilidad a pacientes más antiguos, pero también a otros más recientes con menor probabilidad. En algunos casos la forma de la curva es aplanada, mostrando que la priorización para esos clústeres es más bien uniforme.

Selección de equipo quirúrgico. 133 cirujanos se clasifican según sus especialidades y las intervenciones que realizan habitualmente con mayor frecuencia. Se establece las frecuencias de asistencia y producción para cada cirujano en cada día de la semana y periodo horario. Por simplicidad, los valores de muy baja frecuencia anual (menos de 5 intervenciones) se asignan a cirujanos-cluster de mayor presencia.

Selección de pabellón quirúrgico. Se determinan las frecuencias de uso de los diferentes pabellones para cada clúster, representando la dedicación preferente de las instalaciones sin hacer distinción en la fuente de ingreso.

Suspensiones de cirugías. Debido a que no se cuenta con información detallada de las causas de suspensiones, éstas se modelan de acuerdo a su frecuencia histórica para cada clúster.

3 Validación del Modelo

Se elaboró un modelo de simulación y se definen más de 15 indicadores de desempeño del sistema para su validación: las cantidades de intervenciones quirúrgicas realizadas:

totales, electivas, de urgencia y de otras entradas diferenciadas según horario, clúster, pabellón y cirujano. Además, se verificaron los tiempos de duración de los procesos dentro de las intervenciones quirúrgicas, los tiempos de permanencia en las listas de espera, el tamaño de la lista de espera final, y ranking de priorización de pacientes según clúster. Se utilizan herramientas de estadística descriptiva, análisis de correlación, intervalos de confianza, histogramas y pruebas de inferencia para verificar la validez de las estimaciones.

4 Conclusiones

Se concluye que la modelación del proceso de priorización de pacientes en lista de espera utilizando distribuciones de ranking según clúster de patologías así como las relaciones de cirujanos a patologías y horarios de desempeño reflejan eficientemente el desempeño del sistema y constituyen una herramienta útil y fácil de implementar en el contexto de la simulación del sistema de pabellones quirúrgicos. El modelo permite implementar y evaluar diferentes políticas de operación y configuración del sistema conformado por los pabellones quirúrgicos y las listas de espera de pacientes en un contexto de simulación de procesos por lo que se constituye en un enfoque poderoso y sencillo para el análisis y mejora en la calidad de servicio a los pacientes en espera de intervenciones.

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Determinación de los porcentajes de aportación en el sistema de jubilación de una institución de educación superior mediante un modelo de optimización

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Abstract. Los sistemas de jubilación y pensión en el mundo han sufrido cambios importantes, debido a las imposiciones gubernamentales en varios aspectos. En esta investigación desarrollamos un modelo de optimización lineal para determinar los porcentajes óptimos de aportaciones en un sistema de jubilación diseñado para apoyar a los docentes de una institución de educación superior. Los parámetros que considera el modelo, el cual es desarrollado en el lenguaje LINGO son: la tasa de interés que genera la inversión, la tasa de inflación, los años ahorrados, los años en que se desea tener cobertura, y los salarios de los trabajadores. Los resultados arrojan los porcentajes óptimos de inversión con respecto al salario del trabajador, suponiendo que se desea tener cobertura durante cierta cantidad de años en el futuro y se ha ahorrado durante un periodo de tiempo, al final mostramos un análisis de sensibilidad haciendo que los parámetros antes mencionados tomen valores en ciertos rangos razonables.

Keywords: Higher Education, Linear Programming, Optimization, Retirement.

1 Introducción

Los sistemas de pensión tienen el objetivo de dotar a los trabajadores de un ingreso económico durante su vida post laboral, para que pueda hacer frente tanto a sus gastos de vida, como a diferentes situaciones que se le pueden presentar. Un plan de pensiones, consiste de un arreglo de pagos regulares, generalmente durante la vida laboral de un trabajador, que le permitirá garantizar un ahorro para la edad avanzada (Blanchard and Fischer (1989); Rofman (2005)).

Mientras los países de todo el mundo se encuentran experimentando incrementos nunca antes visto en la esperanza de vida y las tasas de fertilidad, paralelamente se presentan cambios en las normas contables, reducciones de contribuciones y bajos rendimientos financieros. Aunado a lo anterior se suma una alta volatilidad en los mercados financieros lo que impacta de manera directa el poder adquisitivo de los trabajadores. Todos estos elementos han llevado a una caída en los sistemas financieros y a un aumento en las tasas de interés. Los fondos de pensiones del Reino Unido y USA, que tradicionalmente habían tenido asignaciones de capital relativamente altas, han sido duramente afectados (Marco, M., Gregoriou, G. N. and Masala, G. (2010)).

En México, tanto el Instituto Mexicano del Seguro Social (IMSS) como el Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado (ISSSTE) abordan la seguridad social estableciendo dos regímenes claramente diferenciados: el régimen obligatorio y el régimen voluntario. Tradicionalmente creados para brindar un retiro digno a los trabajadores, los sistemas de pensiones en México enfrentan retos enormes, producto de un escenario complejo. En las leyes de ambas instituciones se establece que la seguridad social en el régimen obligatorio debe atender el retiro, cesantía en edad avanzada y vejez de los trabajadores. Puede apreciarse entonces la importancia que históricamente ha otorgado el estado mexicano a los planes de pensiones en nuestro país. No obstante, el modelo tradicional de pensiones ha sufrido diversos cambios debidos a múltiples problemáticas que se han presentado tanto a nivel global como local. El modelo de liberalización financiera imperante en México, desde hace varias décadas, generó que se modificara el sistema de pensiones. En México se reformó el sistema de pensiones para el retiro del IMSS, que desde el año 1997 cambió (IMSS(1997)), de un sistema público, a un sistema privado de aportaciones individuales. Paralelamente, en 2007, se reformó la ley del ISSSTE, (ISSSTE(2007)), de tal manera que la nueva ley permite la creación de un sistema de pensiones que actualmente funciona como una Administradora de Fondo para el Retiro (AFORE).

Como puede verse, la creación de fondos de ahorro para el retiro tiene una importancia enorme desde cualquier perspectiva: social, económica, política y finalmente, humana. El garantizar un nivel de vida digno para los trabajadores pensionados que aportaron su fuerza laboral durante una vida de trabajo, es un problema de la mayor relevancia. La mejoría en los tratamientos médicos para atender enfermedades crónico degenerativas que aquejan de manera importante a los adultos mayores, ha favorecido que la esperanza de vida se incremente de manera significativa, con el consecuente impacto en la calidad de vida de los mismos. Es decir, la longevidad puede tener consecuencias importantes en el plan de pensiones de los trabajadores. Este es un tema en el que tanto legisladores, actuarios e ingenieros financieros tienen que abordar desde sus respectivas disciplinas.

De acuerdo con los datos proporcionados por el IMSS, el ISSSTE y el Instituto Nacional de Estadística Geografía e Informática (INEGI), la proporción de trabajadores activos cotizantes en los sistemas de pensión respecto a la población económicamente activa (PEA) ocupada fluctuó alrededor de 37 por ciento entre 2000 y 2009 (Murillo, S., and Venegas, F. (2011)). Actualmente, cerca del 60 por ciento de la PEA ocupada no está cotizando para acceder a una pensión por jubilación o retiro al llegar a la vejez. Esto, desde luego, conduce a diferentes cuestionamientos sobre las funciones sociales y económicas que los sistemas de pensiones deberían cumplir (Murillo, S., and Venegas, F. (2011)).

Por todo lo anterior, resulta indispensable abordar el tema del ahorro para el retiro con el objetivo de mitigar las condiciones de desamparo en que se encuentra una enorme parte de la población en México al llegar a una edad avanzada. A más de veinte años de la reforma a la Ley del IMSS, es necesario proveer alternativas viables que permitan que los trabajadores puedan contar con un plan de pensión para el retiro.
(Lin C, et al., 2014) hacen uso de un proceso estocástico de Ito, considerando tres variables de estado: la tasa de crédito, la tasa interés libre de riesgo, y la tasa de crecimiento del salario, dicho proceso es estudiado a través de un modelo de simulación tipo Mínimos Cuadrados Monte Carlo (LMS) para fijar los precios de las opciones y en donde el beneficio obtenido se toma del máximo entre los beneficios definidos y las contribuciones definidas. En el modelo se toma como supuesto que la edad máxima para permanecer en el sistema de pensión es de 65 años, sin embargo, también considera que existen dos posibilidades en donde el trabajador se pueda retirar con menos de esa edad: (1) El trabajador tiene más de 15 años de experiencia y más de 55 de edad y (2) el trabajador tiene más de 25 años de experiencia.
En este trabajo se desarrolla un modelo de ahorro para el retiro de los trabajadores académicos de una institución de educación superior pública en México, cuyo objetivo es mitigar las consecuencias económicas que los planes de retiro vigentes (AFORES) con seguridad no van a cubrir. El estudio se plantea desde dos perspectivas: (1) El primero hace un análisis de la cobertura en tiempo que los ahorros alcanzan a cubrir haciendo uso de las aportaciones sugerida por la institución educativa, y (2) Bajo una perspectiva de optimización se determina el mínimo porcentaje del salario que se recomienda aportar para tener determinada cobertura en años, bajo ciertos años de trabajo.

2. Materiales y Métodos

2.1 Descripción del problema.

En el año de 1997 el Instituto Mexicano del Seguro Social (IMSS(2019) publicó una nueva ley para reglamentar las jubilaciones, esta nueva ley surge por diferentes razones, entre ellas podemos encontrar el incremento promedio de la esperanza de vida de los Mexicanos, según el (INEGI (2019)) la esperanza de vida ha aumentado considerablemente; en 1930 las personas vivían en promedio 34 años; 40 años después en 1970 este indicador se ubicó en 61; en el año 2000 fue de 74, en 2016 fue de 75.2 años y especialmente para el año 2016 en el estado de Hidalgo la esperanza de vida fue de 74.6 años. Otro aspecto importante es el origen del recurso económico que se obtiene para las jubilaciones, pues en la antigua ley del Seguro Social, el recurso otorgado a los jubilados provenía de las personas económicamente activas. Si observamos datos proporcionados por el (INEGI(2019)) veremos que el índice de natalidad se redujo en

un 50% entre los años 1970 y 1990, esto ocasiona que si no existen personas económicamente activas para poder subsidiar la jubilación de las personas retiradas se tendría un problema económico de grandes dimensiones al intentar otorgar este recurso.

En dicha ley se menciona que las personas que cuenten con un trabajo formal y que comiencen a trabajar después de julio de 1997 sólo recibirán el dinero ahorrado por ellos mismos en su fondo de retiro (Afore), el cual se otorgara en parcialidades de acuerdo a la esperanza de vida en ese momento. Tomando en cuenta que las recompensas económicas dadas por esos esquemas de retiro (Afores) son bajas, por ejemplo (https://app.finauta.com/retiro/res/fc4af1a0#News), una persona de 43 años en la actualidad, con un salario mensual 20,000 MXN y un ahorro acumulado de 100,000 MXN hasta este momento , estaría recibiendo aproximadamente 3,600 MXN mensuales a los 60 años de edad, casi una quinta parte de su salario actual, además, sin considerar inflación. A la luz de ese escenario, no tan favorable, algunas instituciones han optado por crear su propio sistema de jubilación con el fin apoyar al trabajador. En este trabajo se desarrolló un modelo de optimización que pudiera apoyar la toma de decisiones en una institución de educación superior para implementar un sistema interno de ahorro para el retiro. En concreto nuestro modelo determina el porcentaje del salario del trabajador que debería invertir en un fideicomiso para alcanzar determinados niveles de calidad de vida económica futura. En las siguientes secciones se desarrolla el modelo de optimización, así como los datos de entrada usados en su análisis.

El proceso de ahorro y retiro consiste en el ingreso de docentes que cuentan con edades y salarios diferentes y que deseen ahorrar un porcentaje de su salario para un fondo de retiro que, a lo largo de un tiempo determinado por ellos, dicho dinero es incrementado por los intereses bancarios producidos por un fideicomiso en alguna institución bancaria. Cuando el docente decide retirarse se otorgará el dinero recaudado a lo largo de los años de ahorro para que pueda disfrutar de su vejez.



Fig 1. Proceso general de ahorro y retiro

2.2 Recopilación de datos.

La institución educativa en donde recabamos información estableció que los profesores beneficiados deberían contar con algunas características importantes para poder ingresar a su programa de jubilación.

Como característica primordial el trabajador deberá pertenecer al sindicato de académicos, esto con el fin de que reciba de manera justa y legal todos los beneficios que establece su contrato colectivo de trabajo. Un elemento importante en el modelo es el salario del trabajador, pues estos no son iguales para todos los profesores, porque en las instituciones educativas de nivel superior existen diferentes tipos de plaza con el que es contratado el personal, debido a su experiencia, nivel de estudios, publicaciones realizadas, etc., entre otros factores que definen su categoría de contratación.

Una parte importante en el modelo de optimización es el porcentaje del salario que tanto los docentes, como la institución misma aportarían al sistema de jubilación, en un principio se creyó que un 5% del salario mensual no significaría una reducción considerable en su nivel de vida. Dado que el dinero aportado por los trabajadores e institución se invertiría en algún instrumento financiero, se considera que estos dan una tasa de interés aproximada del 6% anual (Comunicación personal).

También, nuestro modelo toma en cuenta la inflación, el cual es manejado como un parámetro más, pues si una persona planea vivir durante 10 años después de su retiro, con el dinero que puede vivir hoy, se necesita inflar su salario actual para llevarlo a valor futuro. Para este caso se considera una inflación de 3.33% ya que en promedio según el Banco de México (Banxico (2020)) es la inflación anual que sufre el país. Como parte de este razonamiento, y en pro de mejorar los salarios, la institución otorga un incremento aproximado salarial del 3% anual tratando de contrarrestar dicha inflación.

2.3 Formulación del Modelo

A continuación, definimos por medio de la siguiente notación las variables y parámetros del modelo de optimización:

Conjuntos:

i: Conjunto de años ahorrando, i={1,…,N}
j: Conjunto de años con cobertura, j= {N+1,…,n}

Parámetros

N: Número de años que la persona ahorra
n: Número de años que la persona recibe pensión (cobertura)
α: Tasa de incremento salarial
β: Tasa de inflación
κ: Tasas de interés que paga el fideicomiso
θ: Tasa de interés en cuenta de ahorro bancaria
S_0 : Salario inicial

Variables:

γ: Porcentaje de aportación (variable de decisión)
R_i : Retiro en el año j
A_i : Aportación en el año i
S_i : Salario en el año i
B_i : Balance en el año i
B_j : Balance en el año j

Con dichas definiciones, el modelo matemático queda como:

Min $Z= \gamma$

S.A.

$$A_i=S_i(2*\gamma) \text{ , } i=1,..., N \quad (1)$$

$$A_j=0 \text{ , } j=N+1,..., N+n \quad (2)$$

$$S_i= S_{i-1} (1+\alpha), \; i=1,...,N \quad (3)$$

$$S_j=0 \text{ , } j=N+1,..., N+n \quad (4)$$

$$B_i= (B_{i-1} +A_i)(1+\kappa), \; i=1,...,N \quad (5)$$

$$R_j=S_0 \; (1 + \beta)^j, \; j=N+1,..., N+n \quad (6)$$

$$B_j = (B_{j-1} - R_j)(1 + \theta), \quad j=N+1,..., N+n \quad (7)$$

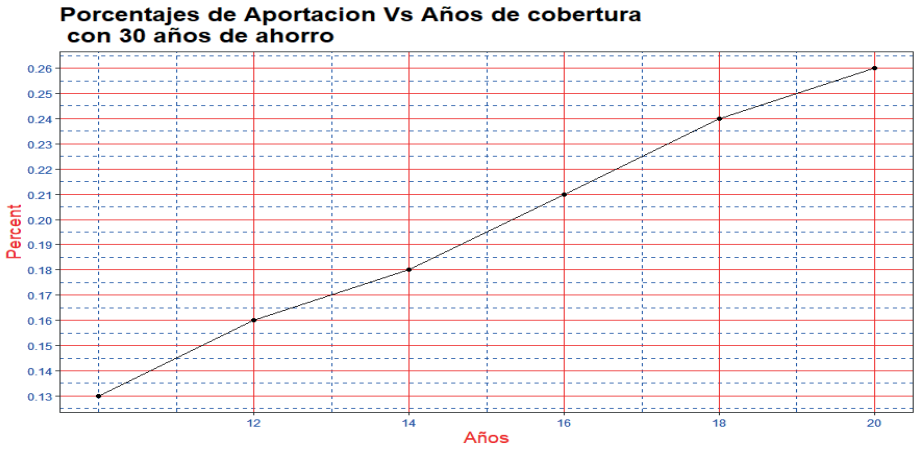
$$R_i=0, \; i=1,..., N \quad (8)$$

$$B_{N+n} \geq 0 \quad (9)$$

$$\gamma \geq 0 \quad (9)$$

3. Resultados y análisis de sensibilidad

El modelo fue ejecutado con los valores de los parámetros siguientes, los cuales fueron explicados en la sección de 2.2:
N=30, n=10, α=3%, β=3.3%, κ=6%, θ=3%, S_0= 240,000.
El porcentaje de aportación obtenido fue de γ=13%, el cual dista por más del doble que se ha propuesto (5%).
Con la finalidad de que los trabajadores y la Institución percibieran el comportamiento del porcentaje de aportación, analizamos dos escenarios, considerando los años trabajados o ahorrados (N) y los años de vida después del retiro que se desean cubrir (n). El primer escenario considera que la persona ahorra un tiempo total de 30 y desea vivir entre 10 y 20 años con el dinero recaudado después del retiro (ver Fig. 2).



Gráfica 2: Porcentajes de aportación según los años de cobertura al momento de retiro

Como se puede observar en la Fig. 2, existe una relación aproximadamente lineal entre los años de cobertura después de la jubilación y los porcentajes de aportación, pues si se desea vivir más años con el dinero generado, el porcentaje de aportación anual deberá ser mayor.
En el escenario número dos se analizó el caso de un profesor retirado que pretende o espera vivir 10 años con el dinero recaudado, pero en esta ocasión el tiempo de ahorro se consideró como variable independiente. En este escenario variamos el tiempo de ahorro desde los 16 años hasta los 30 años, obteniendo los siguientes resultados (véase la Fig. 3).

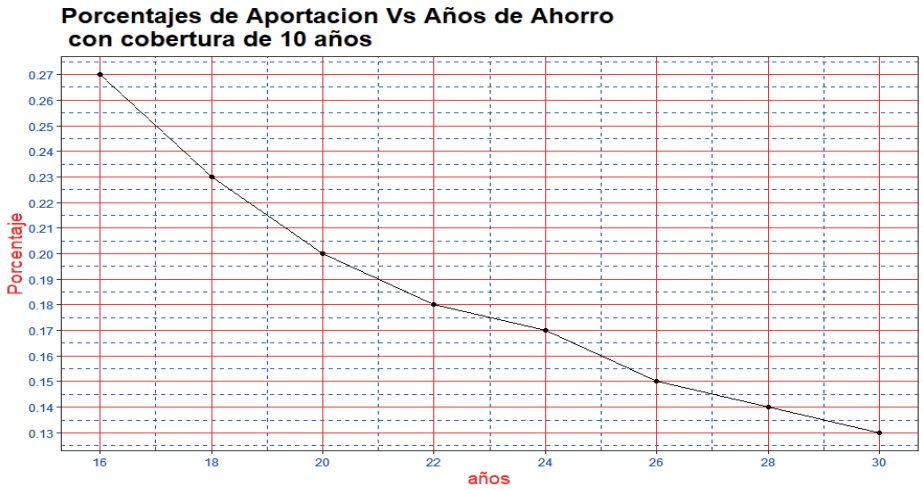


Fig. 3: Relación de años de ahorro y porcentajes de aportación para un retiro con 10 años de cobertura económica

En la Fig. 3, podemos observar que la curva es descendente, por lo tanto, a medida que ahorramos más tiempo el porcentaje de aportación es menor para vivir diez años de jubilación.
Por el momento este modelo no incorpora el efecto que tiene la esperanza de vida del docente, ya que es evidente, en cualquier caso, que, aunque se desee disfrutar del ahorro una cierta cantidad de años, esto puede ser truncado por la muerte del individuo. Estudios futuros podrían incluir un tipo de modelo de programación estocástica, para incluir el factor del tiempo de vida o la aleatoriedad de las tasas de interés, incluso cambiar el enfoque por un modelo de simulación.

4. Conclusiones

El modelo desarrollado permitió a la Institución Educativa definir el mejor porcentaje de aportación salarial, considerando las opiniones de los profesores después de que ellos fueron informados del análisis generado con el modelo. Lo que fue evidente de este análisis es que un porcentaje del 5% de aportación salarial, es insuficiente para cubrir los gastos de vida futuros de la mayoría de los trabajadores. El modelo resulta ser útil para todas aquellas empresas que requieran hacer de una manera cuantitativa un análisis de sus distintos escenarios en sus planes de jubilación. Actualmente se está trabajando por los autores un modelo estocástico de simulación para explorar escenarios más reales en el comportamiento del sistema.

Apendice 1: **Programa en Lingo**

```
SETS:
  IVNA/1..20/:vna;
  IVNC/1..10/:vnc;
ENDSETS
SETS:
  Ahorro:Sa,Aa,Ba;
  Cobertura:Rc,Bc;
ENDSETS
DATA:
  na=40;
  nc=20;
  Ahorro=1..na;
  cobertura=1..nc;
  alfa=.03;
  beta=.033;
  ka=.06;
  kc=.03;
ENDDATA

SUBMODEL BASE:
   !funcion objetivo;
   [AportationRate]Min= gamma;
   !RESTRICCIONES;
   So=240000;
   Sa(1)=So;

    @FOR(Ahorro(t)|(t #GE# 2 #AND#
    t#LE#na):Sa(t)=Sa(t1)*(1+alfa);!salarios;
    @FOR(Ahorro(t)|(t #GT# na): Sa(t)=0);salarios;
    @FOR(Ahorro(t)|(t #AND# t #LE#
    na):AA(t)=Sa(t)*(2*gamma));!aportaciones durante
    ahorro;
    @FOR (Ahorro (t) |(t #GT#
    na):AA(t)=0);!aportaciones durante cobertura;
    Ba(1)=(So*(2*gamma))*(1+ka);! Balance final año 1;
    @FOR (ahorro(t) |(t #GE# 2 #AND# t #LE#
    na):Ba(t)=(Ba(t-  1)+Aa(t))*(1+ka));!balance
    ahorro;
    @For(Cobertura(t) |(t#GE# 2 #AND# t #LE#
    nc):Rc(t)=Sa(1)*(1+beta)^(na+t));!retiros
    cobertura;
    Bc(1)=Ba(na)-Rc(1))*(1+kc);
    @FOR cobertura(t) |(t#GE# 2 #AND# t #LE#
    nc):Bc(t)=(Bc(t-1)-
    Rc(t))*(1+kc));!balance durante cobertura;
    Bc(nc)>=0;
ENDSUBMODEL
```

```
CALC:
     @for(ivna(j):na=20+j;
     @for(ivnc(k):nc=10+k;
     @SOLVE(base));
ENDCALC
```

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Biofilm Formation on Ultrafiltration Membranes by Yeast Strains Isolated from Apple Juice Processing Industries

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Abstract. Four yeast strains (*Candida tropicalis, C. krusei, C. kefyr* and *Rodhotorula mucilaginosa*) isolated from an apple juice plant were evaluated for their ability to form monospecies biofilms on ultrafiltration membranes. Yeast attachment and biofilm formation was estimated at different contact times 2, 6, 24, 48, 72 h and one week using apple juice as food matrix and polyvinylidene fluoride membrane as contact surface. The highest counts recorded after one week trial were for *C. tropicalis* and *C. krusei* (9.02 ± 0.30 and 9.30 ± 0.29 log CFU cm^{-2} respectively), followed by *C. kefyr* (8.63 log CFU cm^{-2}) and *R. mucilaginosa* with the lowest adhesion (7.68 log CFU cm^{-2}). The present study supports the importance to examine the interactions among members of resident microbiota on surfaces commonly used for juice clarification processes and should alert about improving and adopting better cleaning and disinfection protocols as they can represent a serious hygienic-sanitary problem.

Keywords: Biofilms, Yeast, *Candida* spp., Ultrafiltration membranes, Apple juice.

1 Introduction

Microorganisms form microbial aggregates called biofilms able to adhere to different surfaces. Microbial cells are enclosed in an extracellular polymeric matrix that they produce and this determines the microenvironment of the resulting microbial community. Biofilms, represent a perpetual hazard for food industries as they contaminate different stages along the production lines leading to potential equipment damage and/or product contamination [1-2]. Membrane technologies are widely used in food industries for many separation processes such as juice clarification. Ultrafiltration (UF) membranes are characterized by a pore size of 0.001–0.05 μm and molecular weight cut-off (MWCO) between 1 and 300 kDa, retaining most of the suspended solids and microorganisms [3]. One of the major setbacks of filtration technologies is

membrane biofouling, which significantly reduces the filtration flux, shortens the lifespan of membrane and increases energy consumption with the consequent losses of product yield [4-6]. Yeasts are the predominant microorganisms associated with the spoilage of acid fruits and acid food products and so they represent the principal microbial group associated to biofilm formation in related industrial facilities [5]. Taking into account the aforementioned, the present study describes the dynamics of monospecies adhesion and biofilm formation of *C. krusei*, *C. tropicalis*, *C. kefyr* and *R. mucilaginosa* on UF membranes under conditions of industrial relevance.

2 Materials and methods

2.1 Culture conditions.

C. tropicalis, C. krusei, C. kefyr and *R. mucilaginosa* were previously isolated from the surfaces of polyvinylidene fluoride (PVDF) UF membranes, of an apple juice processing industry located in the Alto Valle de Río Negro, Argentina [6]. Stock cultures of each yeast strain were stored at -70°C until use in yeast extract glucose chloramphenicol (YGC; Biokar diagnostics, Beauvais, France) broth supplemented with 20% v/v glycerol. Before use, a loop of frozen cells was suspended in YGC broth at 25 ± 1°C until reaching the stationary phase (48 h). Cultures were then harvested by centrifugation at 1200 x *g* for 5 min (Labofuge 200, Kendro, Germany) and washed twice with phosphate-buffered saline. Pellets were subsequently re-suspended in sterile clarified 12°Brix apple juice and the suspensions were adjusted by optical density at 550 nm to 0.125 (~ 10^6 cells ml^{-1}) using a spectrophotometer (Thermo Spectronic Genesys 20, Thermo Electron Corporation, Waltham, MA, USA).

2.2 Food soiling system (culture media) and biofilm formation

The 12° Brix apple juice used in the successive assays was prepared from 72° Brix concentrated apple juice provided by a national producer/exporter company. Assays were carried out on PVDF-UF membranes (Synder Filtration, Vacaville, CA, USA), with a MWCO of 100 kDa and operation characteristics resembling the ones seen in juice processing industries [3]. According to the supplier's recommendations, before use the membranes were immersed for 15 min in sterile distilled water to eliminate possible antibiotic residues. For the assays sections of 1 x 2 cm of PVDF membranes were cut with sterile scissors and the sections were placed into each well of a sterile 6-well plate (Jet Biofil, Argentina). To test monospecies biofilm formation, 4 ml of each yeast adjusted suspension was put in contact with surfaces for 2, 6, 24, 48, 72 h and 1 week at 25 ± 1 °C under static conditions. Initially, yeast cells were allowed to deposit on the membranes for 2 h at 25 ± 1°C. Afterwards, the food matrix was replaced every 48 h with sterile juice in order to provide fresh nutrients for the cells.

2.3 Quantification of cells and statistical analysis

After each incubation period membranes were carefully removed using sterile forceps and rinsed by immersing in sterile water for 1 min to remove loosely attached cells. The remaining cells were detached following Trampuz [7] with some modifications Briefly, surfaces were transferred to tubes with sterile beads and 9 ml of water and placed in a bath ultrasound (Digital Ultrasonic Cleaner, PS-10A); this was filled with deionized water and specific holders were used to place two tubes on the corner locations. The samples were sonicated for 2 min at 20°C, at a frequency of 40 KHz. Then each tube was vortexed at full speed for 1 min. After that, samples were serially diluted and counts determined by spread plate technique on YGC agar after 24– 48 h incubation. The results were expressed as log CFU cm^{-2}. In all cases, triplicate tests were performed under identical conditions and the results expressed as means and standard deviations (mean± SD). When appropriate, Student's t-test was used for comparison of means. Confidence level equal or higher than 95% was considered statistically significant (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$).

3 Results and discussion

Yeast attachment and biofilm formation on PVDF UF membranes was evaluated at six time interval (2, 6, 24, 48, 72 h and one week), is shown in **Table 1**. After one-week trial, *C. krusei* and *C. tropicalis* were the strains that presented the highest counts. The trend was observed along the different times intervals assayed. Comparing the start point (2 h) with final point (1 week) it was observed that *C. krusei*, *C. tropicalis, C. kefyr* increased 2.09, 2.08 and 1.44 log units respectively while *R. mucilaginosa* increased 0.89 log units at the end of the trial. *C. krusei* represented the majority of the isolates from UF membrane samples and this show the adaptive advantage of this species in this environment [6-9]. *C. tropicalis* is capable of producing multicellular, filamentous forms of growth; it was suggested that the condition to switch their morphology modifies the ability to invade different surfaces to form biofilms [1-2, 8]. These yeasts are able to form a dense network on inert surfaces, forming biofilms resistant to removal. Previously, Tarifa [9] described and characterized the multispecies biofilm formation under a flowing system and observed that the four yeasts species adhere to active part of the membrane and to the fibers. In this work, it was observed that the yeasts strains studied were able to strongly adhere and form mono-species biofilm on the PVDF membrane surface and increased their viable cell counts. Testing different conditions contribute to understand the behavior of theses yeast in diverse environments and conditions.

Table 1. Cells numbers of *R. mucilaginosa, C. tropicalis, C. krusei and C. kefyr* expressed as mean log CFU cm^{-2} ± SD in mono-species biofilms on PVDF-membranes surfaces at different times at 25º C.

Time	2	6	24	48	72	One Week
R. mucilagi-	6.79 ± 0.14	6.84 ± 0.17	7.27 ± 0.28	7.35 ± 0.18	6.71 ± 0.08	7.68 ± 0.35

nosa		ns	ns	*	Ns	***
C. tropicalis	6.94 ± 0.18	7.58 ± 0.24 **	8.33 ± 0.16 ***	8.31 ± 0.08 ***	8.50 ± 0.26 ***	9.02 ± 0.30 ***
C. krusei	7.21 ± 0.22	7.77 ± 0.22 *	8.16 ± 0.23 ***	8.41 ± 0.20 ***	8.90 ± 0.12 ***	9.30 ± 0.29 ***
C. kefyr	7.19 ± 0.18	6.26 ± 0.00 ***	7.52 ± 0.22 ns	7.91 ± 0.23 **	8.22 ± 0.18 ***	8.63 ± 0.32 ***

Significant differences reference are expressed through the following nomenclature ns, not significant, *p <0.05, **p < 0.01 ***p < 0.001, all are in reference at 2 h of own specie.

4 Conclusion

Research on biofilms has focused on understanding the mechanisms and factors governing biofilm formation in mono- or dual-species biofilm models and in the design of strategies to control them at lab scale. The results of this study should alert to the presence of complex communities that could affect the effectiveness of sanitation procedures and the microbiological stability of juice-producing plants. Future studies will focus multispecies biofilm formation on membranes under static conditions and the interactions between common spoilage yeast and bacterial pathogens pertinent to juice safety.

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Modelado Cinético de la Degradación Térmica de Biocompuestos y de Color en Tomate Triturado.

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Resumen. Se estudió el efecto del calentamiento sobre la degradación de color y biocompuestos como ácido L-ascórbico *(AA)* y licopeno *(L)* en tomate triturado a 70, 80, 90 y 100 ºC durante 2 h. Los cambios la coordenada *a** de color (rojo-verde), siguieron una reacción de primer orden con una energía de activación de 64,54 kJ/mol. La degradación de *AA* y *L* también siguieron una cinética de primer orden con energías de activación de 25,69 y 45,96 kJ/mol, respectivamente. Las energías de activación obtenidas revelaron que *a** fue el parámetro de calidad más sensible a los cambios de temperatura, mientras que las constantes de la velocidad de reacción (*k*) mostraron que *L* presenta la mayor velocidad de degradación en comparación con los demás parámetros estudiados. Por otra parte, la relación entre el contenido de licopeno y el color (coordenada *a**) en el tomate triturado, mostró una correlación positiva, la cual se evaluó mediante el coeficiente de Pearson (r = 0,88). Los resultados obtenidos en este estudio podrían ser útiles para optimizar el procesamiento térmico de tomate triturado, minimizando las pérdidas de componentes de calidad nutricional y sensorial del producto.

Keywords: Tomate Triturado, Cinética de Degradación Térmica, Calidad.

1 Introducción

El tomate (*Solanum lycopersicum*) es un fruto climatérico de un color rojo intenso característico. Además de ser uno de los cultivos más significativos del mundo y de gran importancia económica [1], presenta un elevado valor nutricional debido al contenido de biocompuestos como el ácido L-ascórbico y licopeno que le confieren una importante capacidad antioxidante. Estos biocompuestos son beneficiosos para la salud, varios estudios epidemiológicos han informado que la ingesta de estos compuestos en la dieta reduce la incidencia de las enfermedades degenerativas, carcinogénicas y cardiovasculares [2-3]. Particularmente, el licopeno tiene una doble función

en la calidad del tomate ya que pertenece al grupo de pigmentos responsables del color, por lo que además de su propiedad antioxidante influye en la percepción de frescura del tomate que, junto con el color, son los atributos de calidad sensorial más importantes [3]. Por su parte, el tomate representa una de las principales fuentes de vitamina C, la cual posee también propiedades antioxidantes con una función protectora del organismo humano [4]. Como contrapartida, el tomate es un producto altamente perecedero, con una corta vida útil poscosecha, lo que limita su distribución y comercialización.

El tomate triturado como subproducto resulta una alternativa que permite el aprovechamiento integral del fruto y generación de valor. El aprovechamiento de piel, pulpa y semillas del tomate, enriquece el perfil nutricional del producto debido a la contribución de todas las partes constitutivas del fruto. Se informó [2] que además de la pulpa donde se concentra el mayor porcentaje de compuestos antioxidantes, la piel aporta hasta un 28% del contenido de licopeno y un 13% de ácido-L ascórbico y las semillas el 22% y 18% para licopeno y acido L-ascórbico, respectivamente. La producción de tomate triturado requiere del procesamiento térmico, el cual es el principal tratamiento en productos a base de tomate [5]; estos procesos (esterilización, pasteurización y deshidratación) permiten generar productos alimenticios inocuos, de mayor estabilidad y vida útil [6]. Sin embargo, durante el tratamiento térmico, las propiedades nutricionales y sensoriales se ven afectadas por el calor. Debido a la importancia de los atributos de calidad y los beneficios asociados a la salud por parte de los biocompuestos presentes en el tomate, resulta importante la optimización del procesamiento térmico basado en modelos cinéticos de degradación apropiados que permitan asegurar la inocuidad y preservar la calidad.

A pesar de que existe una amplia literatura asociada al estudio de componentes de calidad en tomate y subproductos como pasta, puré, jugos y salsa, no se han encontrado estudios cinéticos en tomate triturado. El conocimiento de los parámetros cinéticos y la energía de activación asociada al proceso térmico son esenciales para poder predecir los cambios de calidad que ocurren durante el procesamiento térmico y optimizar dicho proceso.

En base a lo anterior, el presente trabajo tuvo como objetivo desarrollar las cinéticas de degradación térmica de los componentes de calidad del tomate triturado que podrían ser de utilidad en la optimización del procesamiento térmico para asegurar la inocuidad y minimizar las pérdidas de componentes de calidad. Por otra parte, se buscó desarrollar una relación entre los parámetros de color y el contenido de licopeno en tomate triturado para determinar la reducción de este componente durante el proceso térmico mediante una medición rápida de color en línea.

2 Materiales y Métodos

2.1 Materia Prima y Preparación de Tomate Triturado

Se utilizaron tomates (*Solanum lycopersicum*) obtenidos del mercado local de Villa María, Córdoba (Argentina). Los frutos fueron almacenados a 4 °C hasta su utilización (dentro de las 24 h). Los tomates fueron lavados con agua de grifo para eliminar

la suciedad superficial y posteriormente seccionados en cuartos y triturados mediante multiprocesadora (Smartchef, Peabody, Argentina) para obtener tomate triturado.

2.2 Tratamiento Térmico

Muestras de 3 mL de tomate triturado fueron colocadas en tubos de vidrio con tapa a rosca y sometidas a calentamiento en baño de agua termostatizado con agitación a temperaturas de 70, 80, 90 y 100 ºC, con una precisión de ± 1°C, a diferentes tiempos (0-120 min). Se colocaron termopares en 3 tubos a través de la tapa para monitorear la temperatura dentro de los mismos durante el calentamiento. El tiempo necesario para alcanzar la temperatura de calentamiento requerida (tiempo de subida) fue inferior a un minuto y este período de tiempo se excluyó del análisis de los parámetros cinéticos. Finalmente, los tubos se enfriaron rápidamente en un baño de agua hielo para detener la degradación térmica.

2.3 Determinación de Color

Las muestras de pulpa tratada térmicamente se homogeneizaron mediante vortex y fueron colocadas en una celda de cerámica (3 cm de diámetro) para la determinación del color; la cual se llevó a cabo mediante colorímetro triestímulo (Konica Minoltta CR-400, Tokio, Japón) con una superficie de medición de 8 mm de diámetro y provisto de un observador estándar de 10° y un iluminador estándar D65. La determinación se basó en el espacio de color CIELab, compuesto por tres coordenadas colorimétricas, L^* que representa la luminosidad (0 para el negro y 100 para el blanco), a^* (valores negativos para el verde, valores positivos para el rojo) y b^* (valores negativos para el azul, valores positivos para el amarillo). El instrumento se calibró con una placa blanca estándar (sY=93,2, sx=0,3133, y sy=0,3192) y cada determinación de color se realizó por triplicado.

2.4 Contenido de Licopeno

La determinación de licopeno (L) se realizó mediante espectrofotometría. Primero, 0,5 gramos de tomate triturado fueron extraídos con 5 mL de hexano: acetona: etanol en proporción 2:1:1. La mezcla fue sometida a agitación mediante vortex durante 3 minutos, al resguardo del aire y de la luz y finalmente se agregó 1 mL de agua bidestilada. Posteriormente se extrajo cuidadosamente la fase superior y se medió la absorbancia por espectrofotometría a 503 nm; se utilizó un espectrofotómetro UV-VIS con arreglo de diodos (Analitik jena specord S600, Jena, Alemania) y una cubeta de vidrio con una trayectoria óptica de 1 cm (l). Para el cálculo del contenido de Licopeno se empleó el coeficiente de extinción molar $\varepsilon = 172.000$ L $mol^{-1}cm^{-1}$ [7]. Las muestras se analizaron por triplicado. Los resultados se expresaron como mg L/100 g peso fresco.

2.5 Contenido de Acido L-ascórbico

La determinación de ácido L-ascórbico (*AA*) se realizó mediante HPLC según el procedimiento descripto por Tiwari et al. [8] con pequeñas modificaciones. Primero, se mezcló 1 g de tomate triturado en un tubo centrífugo de 15 mL con 5 mL de ácido metafosfórico al 2,5% (p/v) (Merck, Darmstadt, Alemania), luego se mezcló durante 3 minutos mediante vortex al resguardo del aire y de la luz. Se centrifugó a 5.338,78 RCF durante 10 min a 4 °C, y luego el sobrenadante se filtró a través de un filtro de nylon de 45 µm (GVS Filter Technology, EUA.) y se colocó en un tubo eppendorf de 1 mL protegido de la luz. Finalmente, se inyectaron 20 µl de extracto filtrado en el HPLC. El sistema cromatográfico utilizado se basó en un HPLC (Thermo Scientific ULTIMATE 3000, USA) con bomba cuaternaria y columna C18 (150 x 4,6 mm, 5 µm, PRONTOSIL SPHERIBOND ODS2, Alemania). Se utilizó un detector DAD a una longitud de onda de 245 nm. La fase móvil fue una mezcla 93:7 de 0,5% p/v de ácido metafosfórico y acetonitrilo (ACN) (pH:2), la cual fue bombeada isocráticamente a 1 mL min^{-1}. Los cromatogramas fueron procesados usando el software del Sistema de Datos de Cromatografía Termo Científica (CDS). Los resultados fueron calculados mediante la curva estándar del ácido L-ascórbico (Sigma-Aldrich, San Luis, EUA) y las áreas obtenidas en los cromatogramas. Todas las muestras se analizaron por triplicado y los resultados se expresaron como mg *AA*/100 g peso fresco.

2.6 Modelo Cinético

La cinética de degradación del cambio en las coordenadas de color, el contenido de *AA* y *L* se evaluaron mediante modelos cinéticos de orden cero (Ec.(1)) y primer orden (Ec.(2)).

$$C = C_0 - kt \tag{1}$$

$$C/C_0 = exp\ (-kt) \tag{2}$$

Donde C es el parámetro a estimar, C_0 indica el valor del parámetro en la condición inicial, t es el tiempo de procesamiento térmico, y k es la constante de velocidad a la temperatura T.

La dependencia de k con la temperatura se modeló utilizando la Ecuación de Arrhenius (Ec.(3)).

$$k = k_0\ exp\ (-E_a/RT) \tag{3}$$

Donde k_0 es el factor de pre-exponencial, E_a es la energía de activación, R es la constante universal de los gases (0,00831 kJ mol^{-1} K^{-1}), y T es la temperatura absoluta.

Para estimar los parámetros se utilizaron los valores medios de las determinaciones realizadas por triplicado.

2.7 Análisis Estadístico

Las experiencias se realizaron por triplicado. Los resultados se expresaron como valores medios ± desviación estándar. Los análisis de correlación y el cálculo de las respectivas constantes se realizaron utilizando el programa Microsoft Excel® 2010.

3 Resultados y Discusión

3.1 Características físicas y químicas

Las características físico-químicas del tomate triturado utilizado en el estudio cinético de color y biocompuestos fueron (± desvío estándar): °Brix (20 °C) = 3,78±0,03; humedad (%) = 95,63±0,12; acidez (% ácido cítrico) = 0,53±0,05; pH = 4,48±0,01; Licopeno (mg *L*/100 g peso fresco) = 5,31±1,51; acido L-ascórbico (mg *AA*/100 g peso fresco) = 19,25±3,86. Los valores obtenidos se encuentran dentro del rango reportado en la literatura de tomate [1-9-10].

3.2 Efecto del Procesamiento Térmico en el Color

El tomate presentó un color rojo característico, el cual se determinó por colorimetría CIELab con valores de a^* = 16,32±0,55; b^* = *11,55*±0,41 y L^* =*37,84*±0,85. El calentamiento a las diferentes temperaturas de estudio provocó un efecto adverso sobre las coordenadas colorimétricas a^*, b^* y L^*. En la Fig. 1 se puede observar la evolución de a^* por efecto del calentamiento, este valor colorimétrico es de gran importancia para evaluar la evolución del color del tomate triturado durante el tratamiento térmico ya que representa el color rojo, propio del producto. Los resultados obtenidos para las variaciones de coordenada colorimétrica a^* fueron modelados mediante cinéticas de orden cero (Ec. (1)) y primer orden (Ec. (2)), presentando el modelo cinético de primer orden un mejor ajuste (R^2 =0,93-0,98). Sin embrago, para los cambios en L^* y b^* no se encontraron modelos cinéticos que describan satisfactoriamente la evolución para las diferentes temperaturas y tiempos de estudio (datos no mostrados).

La constante cinética de velocidad (k) fue calculada a partir de las curvas de a^*/a^*_0 en función del tiempo (Fig. 1) y se describe en la Tabla 1.

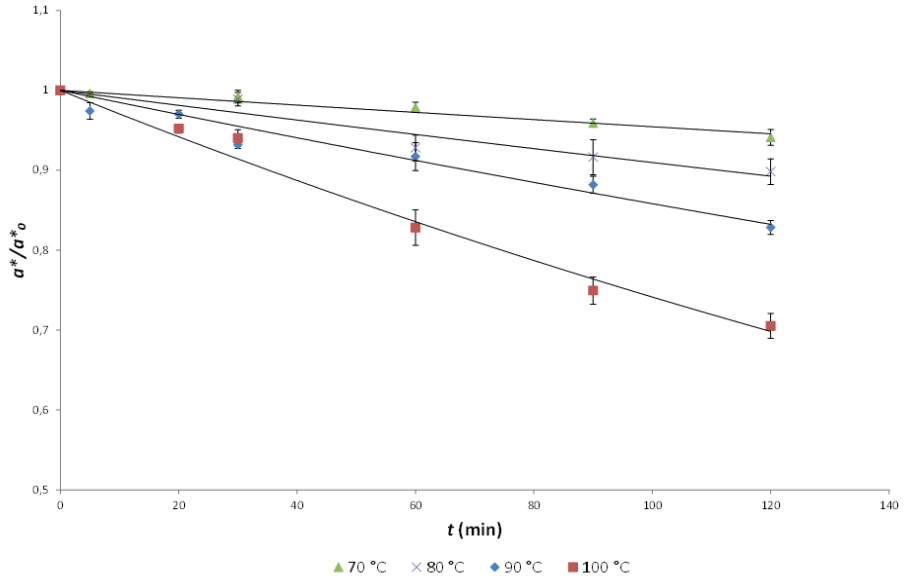

Fig.1. Degradación isotérmica de la coordenada colorimétrica a^* en tomate triturado tratado a diferentes temperaturas. Las líneas representan los ajustes del modelo (Ec. (2)) a los datos experimentales. Las barras representan la media ± desviación estándar.

Se observó que los valores de k aumentaron con la temperatura, lo que indica que la degradación es mayor a temperaturas de procesamiento más elevadas. Los valores de k para los cambios de la coordenada a^* durante el calentamiento se incrementaron con la temperatura, tomando valores de entre 0,5-3,0 x 10-3 min-^{1}. En correspondencia con el presente estudio se informaron cinéticas de primer orden de la coordenada a^* para puré de tomate [11] y pasta de tomate procesados térmicamente [12]. Asimismo, se reportó un modelo cinético de primer orden para los cambios de color en piel de tomate a temperaturas entre 50-100 °C [13].

El valor de a^* para tomate triturado tratado térmicamente a 70, 80, 90 y 100 °C durante 120 min mostró reducciones de 5,89; 10,18; 17,17 y 29,48%, respectivamente. Para evaluar el efecto de la temperatura sobre las constantes cinéticas, los datos mostrados en la Tabla 2 se ajustaron a la ecuación de Arrhenius (Ec. (3)). La energía de activación (E_a) obtenida por Arrhenius es una medida del efecto de la temperatura sobre cada uno de los procesos, de manera que, para un mismo incremento de temperatura, cuanto mayor sea el valor de la energía de activación, mayor será el efecto que produzca; para la coordenada a^* se obtuvo un E_a = 64,54 kJ/mol (Tabla 2). Ganje et al. [12] reportaron un valor similar de energía de activación (65,22 kJ/mol) para el valor de a^* en pasta de tomate tratada térmicamente. A su vez para pasta de tomate doblemente concentrada [14] se reportó un valor de 40,96 kJ/mol. Sin embargo, se informó para piel de tomate tratada térmicamente [13] un valor de E_a = 29,07 kJ/mol, significativamente menor al obtenido en este estudio, lo que podría indicar menor sensibilidad a los cambios de temperatura para la piel de tomate respecto al tomate triturado.

3.3 Degradación Térmica de Licopeno

La concentración inicial promedio de licopeno en el tomate triturado fue de 5,31±1,51 (mg 100 g^{-1} peso fresco), valor que disminuyó con el calentamiento. Se informaron en la literatura contenidos de licopeno similares para piel y pulpa de tomate [2] con valores de 8,7±1,12 y 2,8±0,14 (mg 100 g^{-1} peso fresco), respectivamente. A su vez se obtuvo un contenido de 6,62±0,32 (mg 100 g^{-1} peso fresco) para puré de tomate fresco [5], mientras que para una emulsión de tomate en aceite de oliva [10] se obtuvieron valores de 6,07±0,24 (mg 100 g^{-1} peso fresco). Sin embargo, para tomates frescos variedad Río Grande [15] se reportó un contenido de 50 (mg 100 g^{-1} peso fresco). Esto muestra que se observa una amplia gama de contenidos de licopeno para tomate, lo que puede estar relacionado con la variedad, la madurez y el procedimiento de extracción.

Los resultados mostraron que el calentamiento produjo una disminución del contenido de L para todas las condiciones de estudio, 70, 80, 90 y 100 °C, con pérdidas de 23,94; 30,17; 45,05 y 55,24%, respectivamente para 120 min de tratamiento, indicando una importante pérdida nutricional. A medida que el tiempo del proceso aumentó, la concentración de dicho componente disminuyó (Fig. 2), siendo mayor dicha reducción al incrementar la temperatura de tratamiento.

Se evaluó el ajuste de los modelos cinéticos de orden cero y primer orden y se obtuvo el mejor ajuste para el modelo cinético de primer orden (Ec. (2)), representando adecuadamente el efecto del tratamiento térmico sobre la degradación de *L* en tomate triturado como se muestra en la Fig. 3. El coeficiente de determinación R^2 presentó valores entre 0,91 y 0,98, indicando un buen grado de ajuste del modelo cinético de primer orden a los datos experimentales.

Otros estudios en tomates y frutas reportaron una cinética de primer orden para la degradación de *L*, en pulpa de tomate durante el secado [16], en subproductos del tomate durante el almacenamiento [17]. Una cinética de primer orden también se reportó para la degradación de licopeno en pulpa de tomate [18] y para una variedad de frutos, tal como se informó para el fruto de Guayaba liofilizado durante el almacenamiento a 30°C [19], entre otros.

El efecto de la temperatura sobre las constantes cinéticas (Tabla 1) se evaluó mediante la ecuación de Arrhenius (Ec. (3)). La Tabla 2 muestra los parámetros de Arrhenius, presentando una energía de activación de 45,96 kJ/mol (con un $R^2 = 0,98$). Este resultado indica que la sensibilidad de la variación del contenido de licopeno a los cambios de temperatura es menor que la que presenta la coordenada *a** de color (ya que es 64,54 kJ/mol). Sin embargo, *L* mostró una mayor velocidad de degradación que el parámetro de color, con valores de *k* entre 2,4-8,2 x 10-3 min^{-1}.

Valores similares de energía de activación fueron reportados en la literatura; para tomate secado por aire caliente se informó un valor de E_a = 46,96 kJ/mol [15], para una emulsión de tomate en aceite de Oliva tratada térmicamente [10] se reportó un valor levemente menor al obtenido en el presente estudio de 28 kJ/mol, al igual que en pulpa de tomate almacenada a diferentes condiciones de temperatura se informó valores de entre 19,87-27,74 kJ/mol [18].

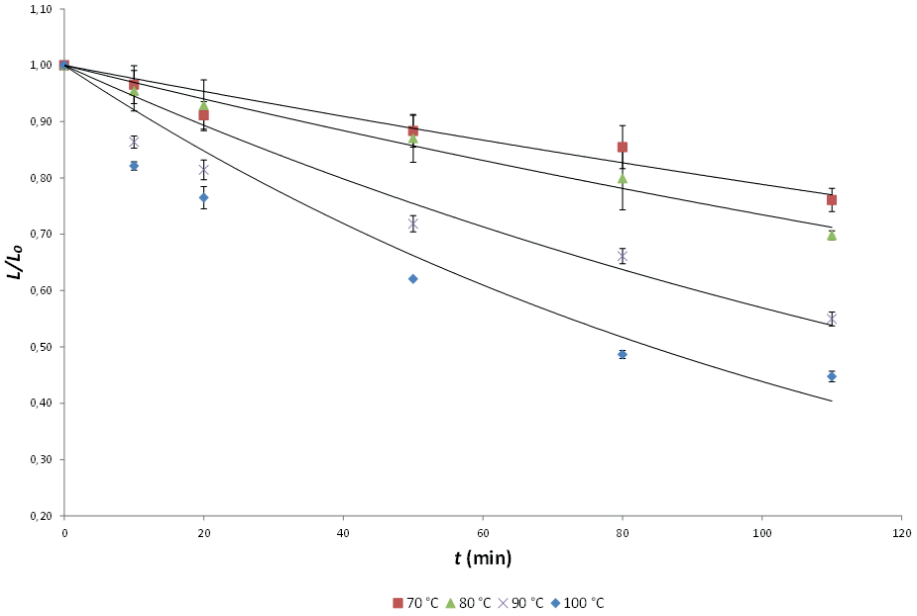

Fig. 2. Degradación isotérmica de *L* en tomate triturado tratado a diferentes temperaturas. Las líneas representan los ajustes del modelo (Ec. (2)) a los datos experimentales. Las barras representan la media ± desviación estándar.

3.4 Degradación Térmica de Acido L-ascórbico

El contenido inicial promedio de ácido L-ascórbico en tomate triturado fue de 19,25±3,86 (mg AA/100 g peso fresco), y se observó una disminución con el calentamiento. Valores similares fueron informados para el contenido de *AA* en piel de tomate [2] reportándose 16,9±0,89 (mg AA/100 g peso fresco), mientras que para piel y pulpa de tomate, de una amplia variedad de cultivares [20], se obtuvieron valores de entre 8,55-56,0 y 8,40-32,4 (mg AA/100 g peso fresco), respectivamente. Dichos autores [20] indicaron que el contenido de ácido L-ascórbico depende de la variedad de cultivares y los factores ambientales. Los resultados obtenidos de los tratamientos térmicos a 70, 80, 90 y 100 °C indicaron una reducción del contenido de ácido L-ascórbico con el procesamiento térmico. Dicha reducción aumentó con el tiempo de tratamiento llegando a valores de 16,43; 17,00; 24,71 y 29,86 % a los 120 min, respectivamente. La degradación térmica del ácido L-ascórbico, para diferentes temperaturas y tiempos de proceso, se evaluaron mediante modelos cinéticos de orden cero y de primer orden, siendo este último el más adecuado para representar esta variación, como se muestra en la Fig. 3. Otros estudios en tomate y frutas también obtuvieron cinéticas de primer orden para representar el efecto del tratamiento térmico sobre el ácido L-ascórbico, este mecanismo de degradación se reportó para tomate secado por aire caliente [15], en tomate para diferentes condiciones de secado y temperaturas [21], para jugo concentrado de tomate durante el calentamiento [22] y pulpa de tomate tratada térmicamente a diferentes temperaturas y tiempos [23]. Además el

modelo cinético de primer orden se reportó para modelar la cinética de degradación térmica de *AA* en una amplia variedad de frutos, en manzanas molidas a altas temperaturas [24], en fruto de Amla durante la cocción a temperaturas entre 50-120 °C [25], entre otros.

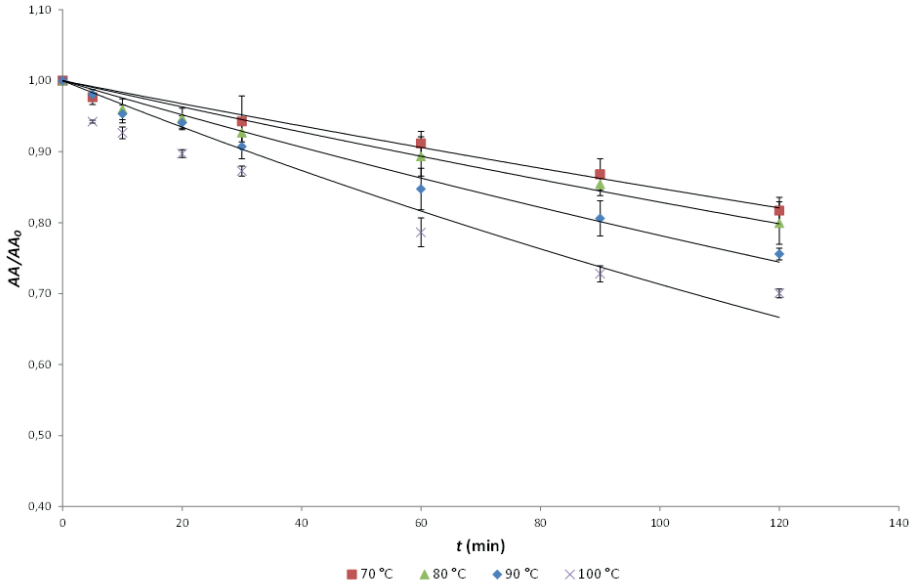

Fig. 3. Degradación isotérmica de *AA* en tomate triturado tratado a diferentes temperaturas. Las líneas representan los ajustes del modelo (Ec. (2)) a los datos experimentales. Las barras representan la media ± desviación estándar.

Como se muestra en la Fig. 3, la degradación térmica del ácido L-ascórbico siguió una cinética de reacción de primer orden, obteniéndose una alta correlación (R^2=0,91-0,99) entre los valores experimentales y los predichos por el modelo para las cuatro temperaturas de estudio, lo que indica la idoneidad del mismo.

El efecto de la temperatura sobre las constantes cinéticas se evaluó mediante la ecuación de Arrhenius (Ec. (3)). En la Tabla 2 se muestran los parámetros del modelo de Arrhenius obtenidos con un alto coeficiente de determinación (R^2 = 0,96). La energía de activación obtenida fue de 25,69 kJ/mol, inferior a la energía de activación obtenida para la coordenada a^* y licopeno, lo que indica una menor sensibilidad a los cambios de temperatura para el ácido L-ascórbico en comparación con los otros parámetros estudiados bajo las mismas condiciones de tiempo y temperatura. Otros estudios informaron energías de activación similares, para jugo de tomate concentrado secado por aire caliente se reportó 28,75 kJ/mol [22], para pulpa de fresa [26] y marula [27] tratadas térmicamente con valores de energías de activación de 21,36 y 29 (kJ/mol), respectivamente. Por otro lado, en un trabajo donde se evaluó la variación de ácido L-ascórbico en tomate durante el secado por aire caliente [15], se obtuvo una E_a de 40 kJ/mol, siendo este valor superior al obtenido en este estudio.

Tabla 1. Parámetros cinéticos y coeficiente de determinación (R^2) para color (*a**), Licopeno (*L*) y acido L-ascórbico (*AA*), en tomate triturado tratado a diferentes temperaturas.

	***T* (°C)**	***k x 10*$^{-3}$ (min^{-1})**	**R^2**
*a**	70	0,47±0,04	0,96
	80	0,94±0,21	0,93
	90	1,53±0,13	0,95
	100	2,99±0,06	0,98
L	70	2,38±0,39	0,93
	80	3,09±0,40	0,98
	90	5,63±0,17	0,91
	100	8,24±0,16	0,91
AA	70	1,65±0,17	0,99
	80	1,88±0,29	0,96
	90	2,46±0,14	0,97
	100	3,38±0,12	0,91

Tabla 2. Parámetros de Arrhenius y coeficiente de determinación (R^2) para color (*a**), Licopeno (*L*) y acido L-ascórbico (*AA*) en tomate triturado.

	***ln* k_0 (min^{-1})**	**E_a (kJ mol^{-1})**	**R^2**
*a**	14,96	64,54	0,99
L	10,00	45,96	0,98
AA	2,54	25,69	0,96

3.5 Relación entre la Coordenada *a** y el Contenido de Licopeno

El color rojo característico del tomate maduro representado por el coordenada *a** está relacionado con el contenido de licopeno, siendo uno de los pigmentos más abundante en el tomate [3-28]. Debido a esta relación, se revelaron cambios de color al evaluar la disminución de *a** durante el procesamiento térmico, e indirectamente esto sugiere que se producen cambios de composición en el tomate triturado, esta relación también

se observó en piel de tomate tratada térmicamente [13]. La Fig. 4 muestra una correlación positiva entre el contenido de licopeno y el valor de la coordenada *a**, durante el tratamiento térmico. Esta relación se evaluó mediante el coeficiente de Pearson, obteniéndose un valor de r = 0,88. A fin de obtener un índice predictivo para estimar las pérdidas por degradación térmica de licopeno midiendo el valor de *a**, la relación entre ambos parámetros se ajustó mediante una regresión lineal, y se obtuvo la siguiente ecuación:

$$y = 0{,}35\ x - 2{,}02 \tag{4}$$

Donde *y* es el contenido de licopeno y *x* la coordenada *a**, durante el tratamiento térmico. Estos resultados sugieren que la coordenada colorimétrica *a** puede utilizarse como un buen indicador de la degradación de licopeno en tomate triturado durante el tratamiento térmico.

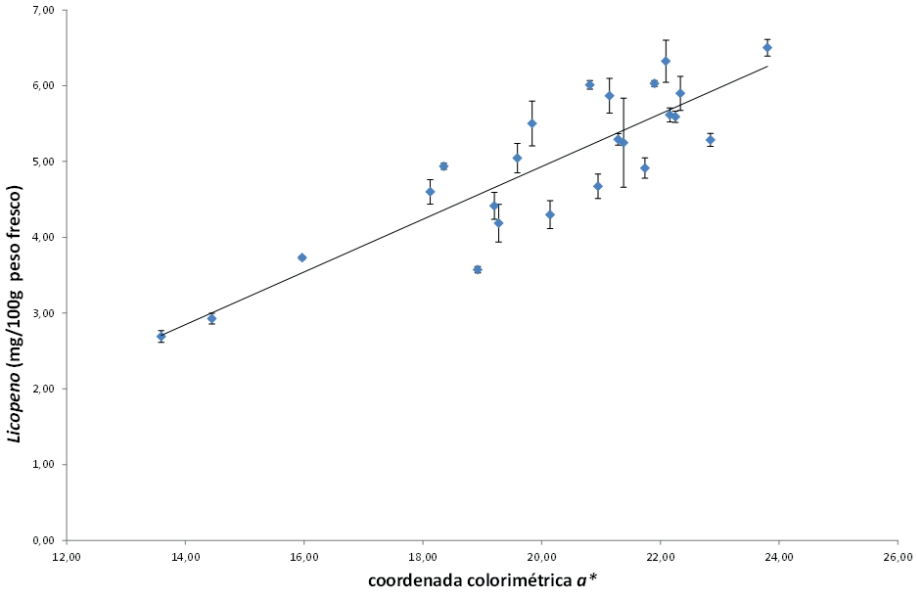

Fig. 4. Relación entre el contenido de licopeno y la coordenada colorimétrica *a**, durante el tratamiento térmico. La línea representa el comportamiento predicho por el modelo lineal (Ec.(4)). Las barras representan la media ± desviación estándar.

4 Conclusión

Este estudio tuvo como objetivo determinar la cinética de degradación térmica de parámetros de calidad como el color y los compuestos bioactivos en tomate triturado como producto que permite un aprovechamiento integral del fruto. El modelo cinético de primer orden fue el que mejor se ajustó a la degradación de color, licopeno y ácido

L-ascórbico. Las variaciones de las constantes de velocidad de degradación con la temperatura se correspondieron en alto grado con la relación de Arrhenius. Las energías de activación obtenidas revelaron que el color, mediante el estudio de la coordenada a^*, fue el parámetro más sensible a los cambios de temperatura, mientras que los valores de las constantes de la velocidad de reacción (k) mostraron que el licopeno tiene la mayor tasa de degradación en comparación con los otros parámetros estudiados. Por otra parte, la relación entre el contenido de licopeno y el valor de la coordenada a^*, por medio de un ajuste lineal, presentó una correlación positiva. Los resultados obtenidos en este trabajo podrían ser útiles para optimizar el proceso de pasteurización de tomate triturado, con la finalidad de reducir al mínimo la pérdida de color y biocompuestos. Por otra parte, la relación entre licopeno y color podría ser de utilidad para obtener, con un buen grado de estimación, el contenido de licopeno en línea mediante una rápida medición de color.

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Evaluación reológica y térmica de oleogeles formulados con ceras de girasol y aceite de girasol alto oleico

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Abstract. En este trabajo se analizaron los perfiles reológicos y térmicos de oleogeles formulados con aceite de girasol alto oleico. Se utilizaron ceras de girasol recuperadas de fondos de tanque de almacenamiento (CP) y ceras de girasol comerciales (CC) como agentes organogelantes. La concentración de las ceras (C) y la temperatura de enfriamiento (T) en base a las cuales fueron formulados los oleogeles se obtuvieron a partir de un diseño de experimentos del tipo factorial de tres niveles con dos variables (3^2), siendo 1,5% y 3,5% la mínima y máxima C, y 5 °C y 25 °C las mínimas y máximas T permitidas. Las propiedades reológicas fueron estudiadas mediante ensayos oscilatorios (barridos de deformación y frecuencia). Todas las muestras presentaron comportamiento del tipo gel, en donde el módulo de almacenamiento fue predominante frente al módulo de pérdida. El oleogel más fuerte y con mayor viscosidad fue obtenido con C = 3,5% y T = 5 °C, siendo indistinto el tipo de cera utilizado. Del análisis de los resultados se determinó que un aumento en la concentración de las ceras provocó un incremento en la propiedad analizada. El mismo efecto fue generado por el descenso de la temperatura de enfriamiento. Las propiedades térmicas fueron analizadas mediante barridos de temperatura y calorimetría diferencial de barrido. En base a los resultados obtenidos se pudo concluir que los oleogeles formulados con CP presentaron propiedades reológicas y térmicas muy similares a las de los oleogeles desarrollados con CC.

Keywords: Oleogel, ceras de girasol, reología.

1 Introducción

Muchos son los riesgos asociados con el consumo de grasas trans y grasas saturadas [1]. Sin embargo, el reemplazo de estas grasas ha demostrado ser un difícil desafío para la industria alimentaria debido a las propiedades sensoriales y fisicoquímicas que éstas le otorgan a los alimentos procesados. Por esta razón, es de suma importancia encontrar reemplazos para las grasas saturadas y trans que posean propiedades organolépticas similares. Una de las alternativas que ha sido ampliamente estudiada es la

generación de oleogeles. Los oleogeles son sistemas conformados por aceites líquidos que son estructurados por agentes gelificantes. En este tipo de compuestos, el aceite líquido permanece inmovilizado dentro de los poros de la red tridimensional que se forma debido al auto ensamblado de los cristales del agente gelificante. Entre las diferentes opciones que se han estudiado, el uso de ceras capaces de estructurar aceites vegetales ha demostrado ser muy prometedor [2].

Los oleogeles de cera se han estudiado como miméticos de grasas en una variedad de productos de la industria alimentaria, incluyendo carne, panadería y productos lácteos entre otros [3, 4]. Específicamente, los oleogeles de cera de girasol se estudiaron como un posible reemplazo para la margarina y los productos para untar [5–7]. Más recientemente, los oleogeles de cera de girasol comenzaron a usarse como un reemplazo total o parcial de las grasas en productos horneados, como galletas y hojaldres [8–10]. Sin embargo, todas estas investigaciones se realizaron a partir cera de girasol comercial como agente organogelante. Los sedimentos del tanque de almacenamiento de aceite de girasol fueron estudiados como una nueva fuente potencial de ceras por Redondas et al. [11]. En base a los resultados obtenidos en ese trabajo, se decidió investigar más a fondo las posibles aplicaciones de este tipo de ceras en la industria alimentaria, específicamente su función como agente gelificante.

Por lo tanto, el objetivo de este trabajo fue estudiar el potencial reemplazo de las ceras de girasol comerciales por las ceras recuperadas de los sedimentos de tanque de almacenamiento de aceite de girasol mediante la comparación de sus propiedades reológicas y térmicas. Con el uso de un diseño experimental factorial de tres niveles con dos variables (3^2), se analizó el efecto de la concentración de las ceras y la temperatura de enfriamiento sobre dichas propiedades de los oleogeles. El comportamiento viscoelástico de los oleogeles fue determinado mediante pruebas oscilatorias (barridos de deformación y frecuencia angular), mientras que su temperatura de gelificación fue medida de manera reológica mediante barridos de temperatura. Finalmente, los perfiles térmicos fueron determinados mediante calorimetría diferencial de barrido.

2 Materiales y métodos

2.1 Materiales

Las ceras de girasol fueron recuperadas de fondos de tanque de almacenamiento de girasol y posteriormente fueron purificadas de acuerdo con el procedimiento desarrollado por Redondas et al. [11]. Las ceras de girasol recuperadas mediante esta técnica serán identificadas con la sigla CP. CP (punto de fusión: 75,13 ± 1,05 °C) se compone de ésteres de cera en el rango de 40 - 60 átomos de carbono (75,9% en peso del total de la muestra cerosa). Las ceras de girasol comerciales (CC) fueron proporcionadas por Koster Keunen Inc. El aceite de girasol alto oleico (GAO) utilizado para desarrollar los oleogeles fue adquirido en un supermercado local.

2.2 Diseño experimental

Con el fin de evaluar la influencia de la concentración de las ceras de girasol (C) y la temperatura de enfriamiento (T) sobre las propiedades reológicas de los oleogeles, se realizó un diseño de experimentos del tipo factorial de tres niveles con dos variables (3^2). Como resultado, se obtuvieron 9 experimentos, los cuales se encuentran reportados en la Tabla 1.

El diseño experimental se llevó a cabo con el software STATGRAPHICS Centurion XVI (prueba LSD de Fisher, $\alpha = 0,05$; versión 16.1.03; StatPoint Technologies, Inc.) [12]. Las concentraciones mínimas y máximas seleccionadas fueron 1,5% y 3,5% en peso respectivamente. El valor mínimo de C (1,5%) se seleccionó en base en los resultados obtenidos en Redondas et al. [11]. En ese trabajo de investigación, los autores encontraron que 1,5% en peso era la concentración mínima de CP necesaria para estructurar completamente GAO. Las ceras de girasol son buenos agentes organogelantes, pero el mayor problema que presenta su uso es que pueden otorgarle a los oleogeles una sensación cerosa en la boca a concentraciones medias y altas [9, 13, 14]. Este problema puede evitarse con el uso de bajas concentraciones de ceras. Es por este motivo que se determinó que 3,5% sea la concentración máxima permitida en el diseño experimental de modo tal de que los oleogeles generados no presentaran dicha sensación cerosa y a su vez tener un buen rango de concentraciones disponibles para evaluar.

Los oleogeles han sido ampliamente estudiados como posibles sustitutos de grasas como la manteca y la margarina. Dado que estos productos se almacenan en heladera a 5 °C, esa temperatura se seleccionó como la temperatura mínima de enfriamiento para el diseño experimental. Además, se propuso el análisis de las propiedades de los oleogeles a 25 °C, también conocido como temperatura ambiente, siendo ésta la máxima temperatura de enfriamiento permitida en este diseño de experimentos.

Tabla 1. Diseño de experimentos utilizado para el desarrollo de los oleogeles

Experimento	C (% peso)	T (°C)
1	1,5	15
2	3,5	5
3	1,5	25
4	3,5	15
5	2,5	5
6	1,5	5
7	2,5	15
8	3,5	25
9	2,5	25

C: concentración de ceras, T: temperatura de enfriamiento

2.3 Desarrollo de oleogeles

Para el desarrollo de los oleogeles (peso final = 50 g), se calentó una determinada cantidad de GAO en un baño de agua hasta alcanzar 80 °C. Se añadió la cantidad correspondiente de ceras, y se mantuvo a la mezcla cera - GAO a 80 °C con agitación magnética constante durante 5 minutos, asegurando la completa disolución de las ceras y la homogeneidad de la mezcla. Posteriormente, los oleogeles fundidos se depositaron en recipientes adecuados para los distintos análisis (recipientes cilíndricos de plástico y cápsulas DSC) y se almacenaron a la temperatura de enfriamiento seleccionada durante 24 h. Finalmente, los oleogeles se mantuvieron a 5 °C durante otras 24 h antes del análisis. Los oleogeles desarrollados con ceras de girasol recuperadas se identificarán con la sigla OCP, mientras que los oleogeles desarrollados con ceras de girasol comerciales se representarán con el acrónimo OCC. Para indicar un experimento específico, el acrónimo (OCP o OCC) irá seguido del número de experimento correspondiente (por ejemplo, OCP1, OCC1, etc.).

2.4 Comportamiento reológico

Las propiedades reológicas de los oleogeles se determinaron mediante un análisis oscilatorio, de acuerdo con el procedimiento descrito por Redondas et al. [11]. Se utilizó el reómetro Paar Physica (MCR 301, Anton Paar Gmbh, Austria) con un sistema de control de temperatura Peltier. Las mediciones se realizaron utilizando la geometría de placa paralela (diámetro = 50 mm, PP50, Anton Paar) con un gap de 1 mm.

Para determinar la región viscoelástica lineal (RVL) de los oleogeles, se realizaron barridos de deformación (γ) en el rango de 0,001 - 100%, a una frecuencia fija de 10 rad/s y a una temperatura de 5 °C. Para investigar el comportamiento de los oleogeles en función del tiempo, se realizaron barridos de frecuencia angular (ω), entre 0,01 - 100 rad/s y un valor fijo de deformación seleccionado dentro del RVL. Finalmente, la temperatura de gelificación de los oleogeles se determinó mediante barridos de temperatura entre 90 y 5 °C con una velocidad de enfriamiento de 2 °C/min, a una frecuencia fija de 6,28 rad/s y un valor de esfuerzo de corte de 0,5 Pa, de acuerdo con el procedimiento descrito por Doan et al. [15].

2.5 Comportamiento térmico

Para determinar el efecto de la concentración de las ceras sobre el comportamiento térmico de los oleogeles, muestras con 1,5%, 2,5% y 3,5% en peso de ceras desarrollados a T = 5 °C fueron analizadas mediante calorimetría diferencial de barrido (DSC). Los procesos de fusión y cristalización de las muestras se estudiaron utilizando un aparato Discovery DSC (TA Instruments, EE. UU.). Las muestras se prepararon colocando entre 8 y 10 mg de oleogel en recipientes de aluminio, que se sellaron herméticamente con una tapa de aluminio y luego se colocaron en la cámara DSC. Para eliminar la historia cristalina de los oleogeles, las muestras fueron equilibradas a 90 °C durante 10 minutos. Luego, las muestras se enfriaron hasta 5 °C a una veloci-

dad de 5 °C/min, manteniendo esta temperatura durante 20 minutos para asegurar la completa cristalización de las ceras. Finalmente, los oleogeles se calentaron hasta 90 °C a una velocidad de 5 °C/min. Se realizaron tres medidas independientes.

La temperatura de fusión (T_f), la temperatura de cristalización (T_c) y sus correspondientes temperaturas de inicio (T_{on}), al igual que la entalpía de fusión (ΔH_f) y la entalpía de cristalización (ΔH_c) se determinaron a partir de los termogramas utilizando el software suministrado con el instrumento (TA Instruments' Universal Analysis Software). Para eliminar la interferencia del ruido en las curvas de cristalización, las mismas fueron suavizadas con el software Origin Pro (OriginLab Corporation) [16]. La entropía de fusión (ΔS_f) se calculó de acuerdo con la ecuación:

$$\Delta S_f = \frac{\Delta H_f}{T_f} \quad (1)$$

2.6 Análisis estadístico

El análisis estadístico de las muestras fue realizado a través de una prueba ANOVA de dos vías y el test LSD Fisher (α = 0,05) con el software de análisis estadístico InfoStat (Versión 2018, Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina) [17].

3 Resultados y discusión

3.1 Módulos de almacenamiento y pérdida

En primer lugar, se determinó el rango viscoelástico lineal (RVL), y para ello los oleogeles fueron sometidos a barridos de deformación. En la Fig. 1 se muestran las curvas representativas de los módulos de almacenamiento (G´) y pérdida (G´´) obtenidas luego de dicho análisis, tanto para OCP (Fig. 1a, 1b y 1c) como para OCC (Fig. 1d, 1e y 1f). En las curvas de G´ se pudieron distinguir dos regiones. La primera región, a bajos porcentajes de deformación, se caracteriza por ser una zona en donde G´ permanece relativamente constante. Esta región, también conocida como "plateau", constituye lo que se conoce como región viscoelástica lineal (RVL). A continuación, se observa una segunda zona en donde G´ disminuye en función del aumento de la deformación aplicado. Esto se debe a que luego de superar el umbral máximo de tolerancia a las deformaciones que las muestras poseen, la estructura cristalina se destruyó y las muestras dejaron de comportarse como un sólido blando para transformarse en un compuesto viscoelástico que fluye.

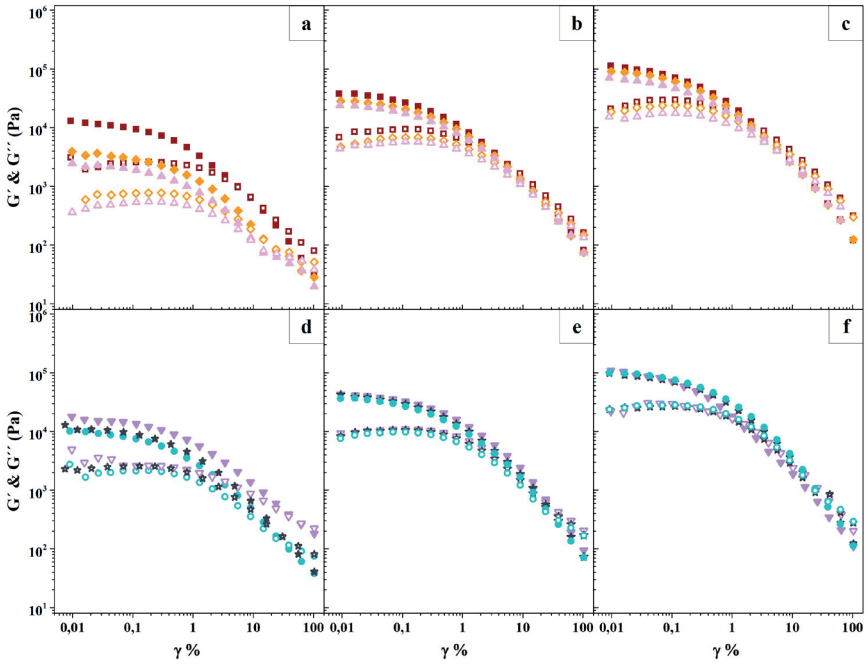

Fig. 1. Variación del módulo de almacenamiento (G´, símbolo lleno) y del módulo de pérdida (G´´, símbolo vacío) en función del barrido de deformación (γ) a ω = 10 rad/s. Los oleogeles fueron desarrollados con 1,5% (a y d), 2,5% (b y e) y 3,5% (c y f) de la correspondiente cera. ■ OCP T = 5 °C, ◆ OCP T = 15 °C, ▲ OCP T = 25 °C, ▼ OCC T = 5 °C, ★ OCC T = 15 °C, ● OCC T = 25 °C. OCP: oleogeles desarrollados con cera de girasol purificada. OCC: oleogeles desarrollados con cera de girasol comercial.

A continuación, se realizaron ensayos de barrido de frecuencia de todas las muestras. Para asegurar la linealidad de la medida, los mismos se realizaron a deformaciones de 0,05%, ya que este valor se encontraba dentro del RVL (Fig. 2). Al analizar los resultados, se pudo confirmar que todas las muestras presentaron un comportamiento del tipo gel con un carácter predominantemente elástico ($G'_{LVR} > G''_{LVR}$). La ausencia de un punto de intersección entre las dos curvas sugiere que las redes cristalinas de los oleogeles toleraron las deformaciones a las que fueron sometidas sin sufrir una ruptura irreparable.

En los reogramas se observó una baja dependencia de ambos módulos con la ω dentro de los límites de la prueba, estando esto indicado por la pendiente ligeramente positiva que las curvas poseen en la Fig. 2. Esto sugiere que los cristales de las ceras se organizan generando estructuras tridimensionales con una alta elasticidad. Malkin e Isayev [18] definieron a los "geles fuertes" como aquellos donde tan δ (ω) ≤ 0,1. Ninguno de los oleogeles analizados en este trabajo satisfizo esta condición (información no mostrada), lo cual indicó que los oleogeles generados en este trabajo se comportaron como "geles débiles".

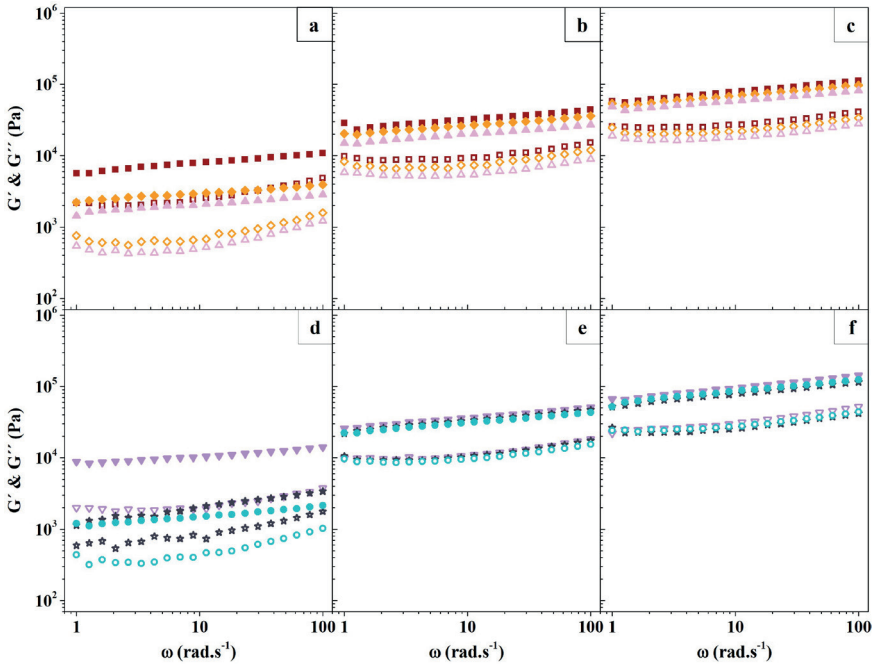

Fig. 2. Variación del módulo de almacenamiento (G´, símbolo lleno) y del módulo de pérdida (G´´, símbolo vacío) en función del barrido de frecuencia angular (ω) a γ = 0,05%. Los oleogeles fueron desarrollados con 1,5% (a y d), 2,5% (b y e) y 3,5% (c y f) de la correspondiente cera. ■ OCP T = 5 °C, ◆ OCP T = 15 °C, ▲ OCP T = 25 °C, ▼ OCC T = 5 °C, ★ OCC T = 15 °C, ● OCC T = 25 °C. OCP: oleogeles desarrollados con cera de girasol purificada. OCC: oleogeles desarrollados con cera de girasol comercial.

Tanto G´ como G´´ aumentaron con el incremento de la concentración, aunque este cambio fue menor en los oleogeles formulados con 2,5% y 3,5% de ceras (OCP: Fig. 2a 2b y 2c; OCC: Fig. 2d, 2e y 2f). Los valores más altos de G´ fueron obtenidos usando 3,5% de ceras. Este hallazgo sugiere que las muestras con la concentración de cera más alta poseían estructuras cristalinas significativamente más elásticas que las estructuras de los oleogeles formulados con concentraciones de cera más bajas, específicamente 1,5%. Esto podría atribuirse a una mayor densidad de cristales. Del análisis de las curvas también se observó una disminución en las propiedades elástica con el incremento de la temperatura de enfriamiento, siendo esta diferencia considerablemente mayor en los oleogeles formulados con 1,5% de OCP y OCC (Fig. 2a y 2d, respectivamente).

En los oleogeles desarrollados bajo las mismas condiciones OCC presentó G´ levemente mayor que OCP, siendo esta diferencia más notoria en los oleogeles formulados con 1,5% de ceras. A pesar de esto, los módulos de OCP y OCC resultaron ser comparables. La composición de ambos agentes gelificantes fue estudiada previamen-

te, determinando que, aunque la distribución de los ésteres de cera era similar, CC presentaba una cantidad ligeramente mayor de ésteres de cera totales [11]. Esto podría explicar las diferencias encontradas durante este análisis reológico.

3.2 Módulo complejo

En los análisis oscilatorios como el barrido de frecuencia angular, G* es una medida de la resistencia total de la muestra a las pequeñas deformaciones aplicadas durante el análisis. En las Fig. 3 se muestran los perfiles de G* a diferentes temperaturas de enfriamiento (5, 15 y 25 °C) y concentración del agente gelificante (1,5; 2,5 y 3,5% peso) en función la frecuencia angular. Todas las curvas resultaron ser lineales y presentaron un leve aumento de G* con el aumento de la frecuencia. Del análisis de los resultados se observó que OCP2 y OCC2 (C = 3,5% de ceras y T = 5 °C) presentaron los mayores valores de G*.

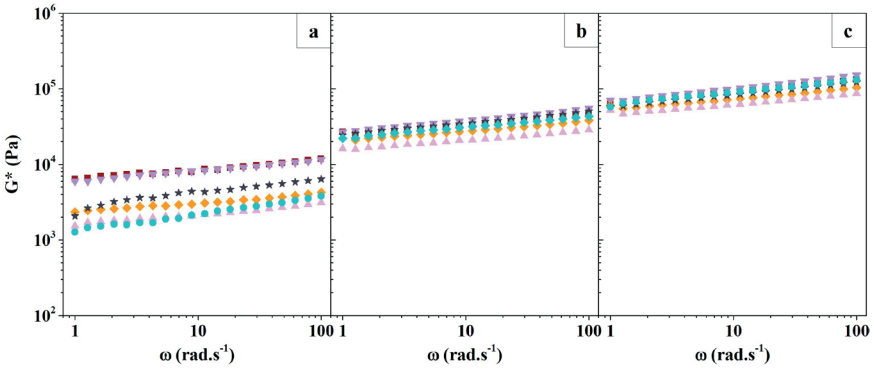

Fig. 3. Variación del módulo complejo (G*) en función del barrido de frecuencia angular (ω) a γ = 0,05%. Los oleogeles fueron desarrollados con (a) 1,5%, (b) 2,5% y (c) 3,5% de la correspondiente cera. ■ OCP T = 5 °C, ◆ OCP T = 15 °C, ▲ OCP T = 25 °C, ▼ OCC T = 5 °C, ★ OCC T = 15 °C, ● OCC T = 25 °C. OCP: oleogeles desarrollados con cera de girasol purificada. OCC: oleogeles desarrollados con cera de girasol comercial.

En la Fig. 3a se puede observar que los oleogeles desarrollados a T = 5 °C presentaron valores de G* considerablemente mayores que aquellos desarrollados a T = 15 °C y T = 25 °C. Este hallazgo indicó que un aumento en la temperatura de enfriamiento generó oleogeles menos resistentes, expresados por menores valores de G*. En cambio, en los oleogeles formulados con 2,5% y 3,5% de ceras el efecto de la temperatura de enfriamiento no fue tan significativo (Fig. 3b y 3c, respectivamente), siendo esto más notorio en los oleogeles con CC como agente gelificante.

3.3 Viscosidad compleja

La viscosidad compleja (η*) provee una medida de la resistencia que poseen las muestras a fluir cuando son sometidas las fuerzas de corte [10]. En todas las muestras se observó una disminución de η* con el incremento de la ω, lo que demostró que η* poseía una gran dependencia de ω (Fig. 4). Este hallazgo es el resultado del reordenamiento microestructural que sufren los oleogeles durante este tipo de ensayos [10]. Patel sugiere que esto se debe a la ruptura de los agregados cristalinos para generar nuevos agregados de menor tamaño que pueden reorientarse en el espacio a lo largo del plano en el cual se aplica la fuerza [19]. De la misma manera que para G´, G´´ y G*, η* aumentó con el incremento en la concentración de las ceras y la disminución de la temperatura de enfriamiento (Fig. 4), siendo esto último más evidente en los oleogeles formulados con 1,5% de ceras (Fig. 4a). Al comparar los oleogeles desarrollados bajo las mismas condiciones, OCC presentó valores de η* levemente mayores que OCP, aunque estas diferencias fueron menos notorias en los oleogeles formulados con 2,5% y 3,5% de ceras, lo que indicó que a estas concentraciones la η*, y por lo tanto la resistencia a fluir, de OCP y OCC fue prácticamente la misma.

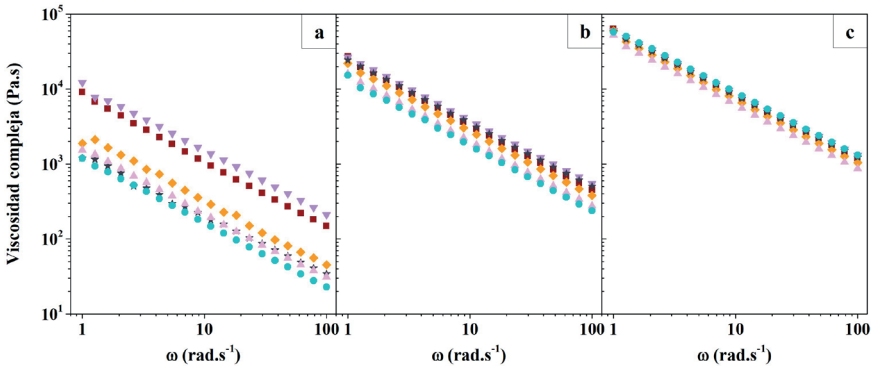

Fig. 4. Variación de la viscosidad compleja (η*) en función del barrido de frecuencia angular (ω) a γ = 0,05%. Los oleogeles fueron desarrollados con (a) 1,5%, (b) 2,5% y (c) 3,5% de la correspondiente cera. ■ OCP T = 5 °C, ◆ OCP T = 15 °C, ▲ OCP T = 25 °C, ▼ OCC T = 5 °C, ★ OCC T = 15 °C, ● OCC T = 25 °C. OCP: oleogeles desarrollados con cera de girasol purificada. OCC: oleogeles desarrollados con cera de girasol comercial.

3.4 Comportamiento térmico

El último análisis reológico realizado fue el barrido de temperatura entre 90 y 5 °C. A 90 °C los oleogeles presentaron un comportamiento líquido, en donde el predominio estaba dado por G´´. Durante el enfriamiento de las muestras se observó un cambio drástico en la pendiente de la curva. Este punto fue definido como $T_{gel\ onset}$ y correspondió a la transición de mezcla líquida a solución viscosa. Al enfriarse por debajo de $T_{gel\ onset}$, la solubilidad de las ceras en GAO comenzó a disminuir, lo que condujo a la nucleación y, finalmente, al crecimiento de los cristales de las ceras. Como resultado,

G´´ y G´ comenzaron a aumentar, hasta alcanzar en punto en donde G´ = G´´. Es en este punto en donde la red tridimensional de los oleogeles se forma debido a la interacción de los cristales. La temperatura en donde ocurre dicho cambio en las propiedades es definida como la temperatura de gelificación (T_{gel}). A temperaturas inferiores a T_{gel}, G´ es mayor que G´´, indicando el carácter predominantemente elástico de los oleogeles.

Los valores de T_{gel} y $T_{gel\ onset}$ de OCP y OCC se encuentran reportados en la Tabla 2. Un aumento en la concentración de CP dio como resultado un aumento de T_{gel} y $T_{gel\ onset}$. En cambio, en OCC se observó que los oleogeles formulados con 2,5% y 3,5% de ceras no presentaron diferencias significativas en sus correspondientes valores de T_{gel} y $T_{gel\ onset}$. Los oleogeles formulados con 2,5% y 3,5% de CP presentaron valores de T_{gel} entre 1 °C y 3 °C mayores que en los oleogeles formulados con CC bajo las mismas condiciones. Este hallazgo sugiere una formación tardía de la red tridimensional de OCC frente a OCP, probablemente debido a las diferencias entre la composición de CP y CC previamente estudiadas [11].

Table 2. Temperatura de gelificación obtenida a partir de análisis reológicos de barridos de temperatura.

	OCP		**OCC**	
C (% peso)	**T_{gel}**	**$T_{gel\ onset}$**	**T_{gel}**	**$T_{gel\ onset}$**
1,5	$47,82 \pm 2,84^{a}$	$51,29 \pm 1,82^{a}$	$48,35 \pm 1,57^{a}$	$50,64 \pm 0,56^{a}$
2,5	$53,30 \pm 0,85^{b}$	$55,12 \pm 0,91^{b}$	$52,19 \pm 0,39^{b}$	$54,21 \pm 0,39^{b}$
3,5	$55,22 \pm 1,13^{c}$	$56,96 \pm 0,72^{c}$	$52,21 \pm 0,49^{b}$	$53,87 \pm 0,58^{b}$

Los valores se reportan como el promedio ± intervalo de confianza (n = 3). Los valores en la misma columna seguidos por diferentes letras (a - c) son estadísticamente diferentes ($p < 0,05$) de acuerdo al test de Fisher. C: concentración de ceras, T_{gel}: temperatura de gelificación, $T_{gel\ onset}$: temperatura inicial de gelificación.

A continuación, se evaluó el efecto generado por la concentración sobre el perfil térmico de los oleogeles, analizados mediante DSC. Para ello, tres muestras de los oleogeles formulados con las concentraciones utilizadas en este trabajo y 5 °C fueron analizados (1,5%: OCP2 y OCC2, 2,5%: OCP5 y OCC5 y 3,5%: OCP6 y OCC6). La temperatura de fusión (T_f) y de cristalización (T_c), así como la entropía de fusión y de cristalización (ΔH_f y ΔH_c, respectivamente) y sus respectivas temperaturas de inicio (T_{on}) se encuentran reportados en la Tabla 3.

Todas las muestras analizadas presentaron un solo pico correspondiente a la fusión de los ésteres que conforman a las ceras de girasol (Fig. 5a). En un trabajo publicado anteriormente, se estudió el comportamiento térmico de las ceras, y se descubrió que en los termogramas de fusión las mismas presentaban picos largos y estrechos debido a su gran homogeneidad química [11]. Durante el proceso de cristalización, los ésteres de cera de las muestras cristalizaban a una T_c ligeramente diferente, generando lo que podría describirse como picos superpuestos. Los oleogeles formulados con CP y

CC presentaron este mismo patrón de cristalización, siendo esto más notorio a medida que aumentaba la concentración de las ceras (Fig. 5b). Doan et al. [20] definió a los oleogeles como disoluciones compuestas por ceras diluidas en aceite. Por lo tanto, es esperable la presencia de múltiples picos superpuestos en los termogramas de cristalización de los oleogeles.

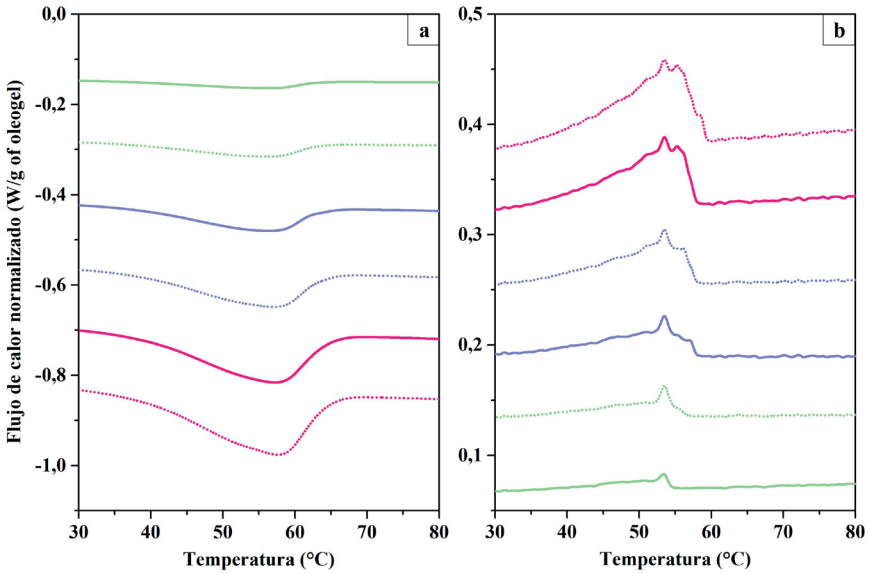

Fig. 5. Perfiles de fusión (a) y cristalización (b) de OCP (línea continua) y OCC (línea punteada) a C = 1,5% (—), C = 2,5% (—) y C = 3,5% (—) de la correspondiente cera de girasol.

Los picos de fusión y cristalización de OCP y OCC fueron más bajos y anchos que los de CP y CC, respectivamente. La temperatura de fusión de los oleogeles fue menor que la reportada para CP y CC (75,13 ± 1,05 °C y 76,86 ± 0,54 °C, respectivamente) [11], debido a la dilución de las ceras en el aceite. De manera similar, la temperatura de cristalización también se ubicó a menores valores que los de CP y CC (72,12 ± 0,56 °C y 70,96 ± 0,57 °C, respectivamente). T_m y T_c aumentaron con el incremento en la concentración de ceras, debido a la presencia de una mayor cantidad de componentes cristalinos (Tabla 3). El mismo comportamiento fue reportado por Blake et al. [21] en oleogeles desarrollados con CC en aceite de canola, Yilmaz y Öğütcü [22] en oleogeles formulados con CC y aceite de oliva y Doan et al. [23] en oleogeles de CC y aceite de salvado de arroz.

Table 3. Comportamiento térmico de oleogeles formulados con aceite de girasol alto oleico y ceras de girasol purificadas (OCP) y ceras de girasol comerciales (OCC).

OCP							
C_{CP} (% peso)	**T_c (°C)**	**ΔH_c (J/g)**	**$T_{on\ c}$ (°C)**	**T_f (°C)**	**ΔH_f (J/g)**	**$T_{on\ f}$ (°C)**	**ΔS_f [mJ/(g.K)]**
1,5	53,04±3,23^{a}	3,01±0,23^{a}	55,49±5,01^{a}	55,42±0,41^{a}	3,34±0,47^{a}	36,01±7,15^{a}	10,17±1,44^{a}
2,5	56,58±2,19^{b}	4,94±0,59^{b}	57,41±1,19^{ab}	57,55±1,52^{b}	4,68±0,56^{b}	37,68±0,59^{ab}	14,16±1,69^{b}
3,5	58,38±1,28^{b}	6,63±0,71^{c}	59,52±1,38^{b}	58,66±1,01^{b}	5,50±0,29^{c}	37,60±0,76^{b}	16,58±0,82^{b}
OCC							
C_{CP} (% peso)	**T_c (°C)**	**ΔH_c (J/g)**	**$T_{on\ c}$ (°C)**	**T_f (°C)**	**ΔH_f (J/g)**	**$T_{on\ f}$ (°C)**	**ΔS_f [mJ/(g.K)]**
1,5	52,20±4,57^{a}	3,09±1,23^{a}	55,73±3,65^{a}	56,66±4,04^{a}	3,19±0,11^{a}	34,59±1,39^{a}	9,28 ±1,81^{a}
2,5	53,65±6,11^{a}	4,74±0,65^{b}	57,25±4,52^{a}	57,46±4,16^{ab}	5,23±0,19^{b}	39,93±0,07^{b}	15,83 ±0,61^{b}
3,5	55,80±1,94^{a}	5,12±0,68^{b}	57,31±1,74^{a}	58,32±1,86^{b}	7,08±0,72^{c}	39,42±1,50^{b}	21,34 ±2,05^{c}

Los valores se reportan como el promedio ± intervalo de confianza (n = 3). Para cada sección de la tabla, los valores en la misma columna seguidos por diferentes letras (a - c) son estadísticamente diferentes ($p < 0,05$) de acuerdo al test de Fisher. C_{CP}: concentración de CP, C_{CC}: concentración de CC, T_c: temperatura de cristalización, ΔH_c: entalpía de cristalización, $T_{on\ c}$: temperatura inicial de cristalización, T_f: temperatura de fusión, ΔH_f: entalpía de fusión, $T_{on\ f}$: temperatura inicial de fusión.

En general, OCC presentó una mayor entalpía de fusión que OCP (Tabla 3). Este hallazgo estuvo en concordancia con ΔH_f de CP (167,71 ± 9,05 J/g de cera) y CC (213,98 ± 16,79 J/g de cera) previamente reportado en Redondas et al. [11]. ΔH_f es considerado como un indicador de la cantidad de material organogelante y de la interacción entre los cristales de las ceras. Como se mencionó previamente, CP y CC presentaban cantidades similares de ésteres de ceras, por lo tanto, un valor más alto de ΔH_f sugiere que OCC presentaba una red tridimensional con una mayor cantidad de interacciones entre los cristales de las ceras y una mejor organización espacial.

Blake et al. mencionó en su trabajo que la entropía de fusión (ΔS_f) proporciona una visión más precisa acerca del orden cristalino, ya que valores más altos de entropía fueron encontrados en oleogeles que presentaban redes con un mayor orden cristalino [21]. Los oleogeles desarrollados con 1,5% de ceras presentaron los ΔS_f más bajos, mientras que los oleogeles con 3,5% de ceras presentaron los valores más altos (Tabla 3). No se observaron diferencias significativas entre los valores de entropía de OCP y OCC formulados con 1,5% y 2,5% de ceras, pero sí existieron diferencias en los oleogeles formulados con 3,5% de ceras, confirmando que, para esta concentración, la red tridimensional de OCC poseía un mayor grado de orden cristalino.

4 Conclusiones

Todas las muestras presentaron un comportamiento de sólido viscoso, con un carácter predominantemente elástico y valores de G´ > G´´ a lo largo de los límites de frecuencias analizado. Se pudo comprobar que, en las muestras desarrolladas bajo las mismas condiciones, OCP presentaba propiedades similares a OCC. En los casos en donde se observaron diferencias, las mismas fueron mínimas, siendo OCC el que poseía el mayor valor. En base a los resultados, se determinó que la concentración de ceras fue el parámetro que más afectó a las características reológicas (G´, G´´, G* y η*) y térmicas (T_{gel}, T_f, ΔH_f, T_c y ΔH_c) de los oleogeles. Se estableció que un incremento en la concentración de ceras produjo un aumento en el parámetro reológico o térmico analizado. También, se pudo establecer que la temperatura de enfriamiento ejerció un efecto del tipo negativo (un incremento en la temperatura provocó una disminución en el valor del parámetro evaluado), siendo este efecto más notorio en los oleogeles formulados con 1,5% de ceras de girasol. Los oleogeles desarrollados con 3,5% de ceras y 5 °C fueron los que presentaron mayores valores reológicos y térmicos.

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Efecto de la Sustitución Parcial de NaCl con KCl Sobre las Propiedades Sensoriales de Queso Port Salut.

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Resumen. En este trabajo se evaluaron y compararon las propiedades sensoriales de un queso Port Salut, con sustitución de un 50% de NaCl con KCl y dos muestras del mismo queso sin sustituir (uno elaborado idénticamente al sustituido, pero de concentración estándar de NaCl, y el otro de una marca comercial líder). Las características sensoriales más distintivas de ambos tipos de quesos fueron evaluadas mediante un panel no entrenado, a partir de una prueba de ordenamiento de atributos. También se determinó la aceptabilidad del queso reducido, en comparación con su versión no reducida, cuando las muestras no fueron identificadas y también cuando lo estaban. Además, en este último caso, a la muestra reducida se le asocio una promesa nutricional. Los evaluadores detectaron diferencias en cuanto al sabor salado y amargo, al compararlo con las muestras no reducidas. La aceptabilidad del queso reducido fue mayor que su versión sin reducción, y la misma aumentó cuando a los evaluadores se le presentó la muestra identificada y con una promesa nutricional de impacto positivo para la salud.

Palabras clave: Queso Port Salut, Cloruro de Sodio, Evaluación Sensorial.

1 Introducción

El cloruro de sodio (NaCl) cumple diversas funciones en los alimentos, como facilitar su procesado, desarrollo y potenciación del sabor, y su conservación; estas características sumadas a que es un ingrediente relativamente de bajo costo, han llevado a su gran utilización [1]. Sin embargo, el consumo excesivo de sal se ha relacionado con la hipertensión arterial (HA) y un mayor riesgo de padecer enfermedades cardiovasculares. Es por esto, que el contenido de sodio de los alimentos procesados es considerado un problema de salud pública; actualmente la ingesta de NaCl en países desarrollados varía entre 8 a 13 g por día, que es muy superior a los 5 g recomendados por la Organización Mundial de la Salud (OMS) [2].

La sal en el queso participa en la formación del sabor, conservación, propiedades funcionales (capacidad de fusión, estiramiento y flujo), reología y textura [3]. Por este

motivo, una reducción en el contenido de la misma implica también mantener las propiedades inherentes al queso. El NaCl puede ser sustituido parcialmente por otros compuestos como cloruro de potasio (KCl), cloruro de calcio ($CaCl_2$) o cloruro de magnesio ($MgCl_2$), siendo el KCl, quien presenta mejores características para la sustitución, debido a la similitud entre los cationes potasio y sodio [4]. Además, numerosos estudios han demostrado que una ingesta de potasio en la dieta puede disminuir el efecto de la HA inducida por el sodio, al disminuir la presión arterial y reducir la excreción urinaria de calcio [5].

En base a lo anterior, los objetivos del presente trabajo fueron evaluar y comparar sensorialmente un queso Port Salut con sustitución de un 50% NaCl con KCl y dos muestras del mismo queso sin sustituir (uno elaborado idénticamente al sustituido, pero de concentración estándar de NaCl y el otro, de una marca comercial líder)

2 Materiales y Métodos

Para las pruebas, se elaboró un queso Port Salut sustituido en un 50% su contenido de NaCl por KCl y otro sin reducción. También se utilizó una muestra de queso Port Salut de una marca líder de la región (NOALSA), con el objetivo de evaluar los atributos sensoriales. Las muestras presentaban un estadio de maduración similar.

2.1 Análisis sensorial

2.1.1 Prueba de ordenamiento por atributos

Un panel conformado por 32 evaluadores (no entrenados), recibieron tres muestras de queso Port Salut ordenadas al azar y codificadas con un número de tres cifras. En esta prueba los atributos evaluados fueron: resistencia al corte, sabor salado, sabor amargo, persistencia del sabor y retrogusto.

2.1.2 Prueba de aceptabilidad

Cuarenta personas que consumían queso Port Salut con una frecuencia mayor a una vez cada dos semanas fueron reclutadas. En esta prueba se evaluaron únicamente los quesos Port Salut elaborados con sustitución en un 50% su contenido de NaCl por KCl y sin reducción (no se consideró el queso de marca comercial).

Los evaluadores fueron divididos en dos grupos de 20. Una mitad realizó la prueba a “ciegas”, sin saber de qué muestras se trataba, mientras que el resto efectuó la prueba con las muestras identificadas y además la reducida en sodio presentaba la siguiente promesa nutricional: “menos sodio más salud”. Cada evaluador recibió, una muestra de queso Port Salut concentración estándar de sodio y otra reducida en sodio, y evaluó la aceptabilidad de cada queso mediante una escala hedónica del 1 al 10, donde 1 representaba la menor aceptabilidad y 10 la mayor aceptabilidad

2.2 Análisis estadístico

Se realizó el test de Friedman para los datos de la prueba de ordenamiento por atributos, tomando como referencia el estadístico *ji-cuadrado* de 4.61 y un valor de significación del 0.1. Aquellos atributos donde se observó diferencia, se evaluaron a partir de un ensayo de múltiple comparación.
El Análisis de Varianza (*ANDEVA*) para dos factores con varias muestras por grupo se realizó para el ensayo de aceptabilidad; en cada uno hubo 20 repeticiones. Los dos factores considerados fueron el tipo de queso Port Salut (reducido o no) y si las muestras estaban identificadas o no. Se empleo el programa informático Excel (Microsoft Office Profesional Plus 2019) para el análisis de datos.

3 Resultados

3.1 Prueba de ordenamiento por atributos

La Tabla 1, muestra la suma de los ordenamientos que le otorgaron los evaluadores a cada muestra de quesos Port Salut, frente a cada atributo. Donde aquella muestra que presento menor sabor salado, los evaluadores le daban el primer orden, mientras que la más salada el tercero. El mismo procedimiento fue aplicada a los demás atributos.

Tabla 1. Valores de la suma de los ordenamientos.

Atributo	PS no reducido	PS reducido	PS marca líder	F experimental
Resistencia al corte	74[b]	62[a, b]	56[a]	5.25
Sabor salado	55[a]	76[b]	61[a]	7.31
Sabor amargo	68[a]	52[b]	72[a]	7.00
Persistencia del sabor	64 [a]	72 [a]	56 [a]	4.00
Retrogusto	60 [a]	72 [a]	60 [a]	3.00

PS: queso Port Salut.
[*]Para un mismo atributo, valores con una letra en común no son significativamente diferentes (p>0.1).

Tal como lo indica la Tabla 1, la muestra reducida en su contenido de sodio se diferenció de las otras dos en cuanto al sabor salado, comportamiento que era esperado. Por su parte, los quesos sin reducción no lograron diferenciarse tras el análisis. El mismo comportamiento se obtuvo para el sabor amargo. Lo anterior indica que el porcentaje de reducción de NaCl y sustitución por KCl es percibido y diferenciado sensorialmente.

3.2 Prueba de aceptabilidad

El queso Port Salut reducido en sodio obtuvo una mayor aceptabilidad, tanto cuando la prueba fue realizada a ciegas como cuando las muestras estaban rotuladas (Ver Fig.1). Los resultados obtenidos indican que tanto en la evaluación de las muestras a ciegas

como cuando estaban identificadas, el queso Port Salut reducido en sodio obtuvo la mayor aceptabilidad.

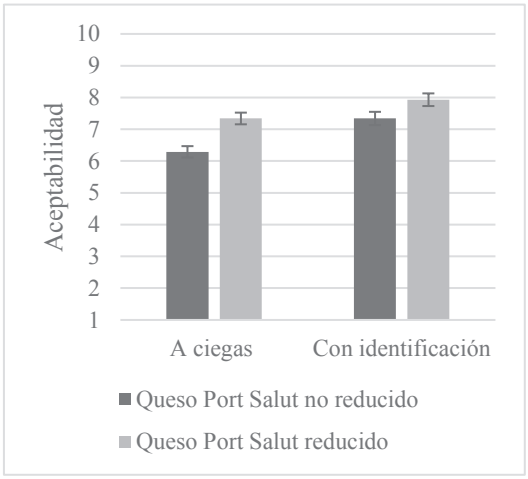

Fig. 1. Aceptabilidad queso Port Salut con y sin reducción de sodio.

4 Conclusión

La sustitución del 50% de NaCl por KCl en queso Port Salut, que fue comprobado al determinar el contenido de sodio en la masa, fue percibida por el panel sensorial a través de la diferencia percibida en el sabor salado y amargo, en comparación al queso no reducido. El reemplazo impactó positivamente en la aceptabilidad del producto, viéndose incrementada cuando se le asociaba a la muestra un efecto positivo a la salud.

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Bioactividad de extractos de bagazo de cerveza

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Resumen. El bagazo de cerveza, mayor subproducto de la producción de cerveza, constituye actualmente un residuo que se descarta o destina a alimentación animal. Sin embargo, su contenido relativamente elevado de compuestos fenólicos lo posiciona como una fuente interesante de estos compuestos bioactivos a ser explotada. En el presente trabajo se estudió el efecto del tiempo de secado al que se sometió al bagazo, cuyo contenido de humedad inicial al egresar del proceso es extremadamente elevado, sobre la bioactividad de los extractos obtenidos posteriormente a partir de dicho material. Se encontró que la extensión del tiempo de secado de 5 a 20 horas produjo una disminución en la calidad de dichos extractos, determinada por el contenido de fenoles totales, la actividad antioxidante y la capacidad antirradicalaria.

Palabras clave: Bagazo de Cerveza, Compuestos Bioactivos, Actividad Antioxidante.

1 Introducción

El bagazo de cerveza (en adelante BSG, por su sigla en inglés 'brewer's spent grain') es el subproducto sólido que se obtiene en la etapa de generación del mosto a partir de la malta de cebada en el proceso de elaboración de la cerveza. Constituye el mayor subproducto de la industria cervecera, representando el 85 % del total de los productos secundarios generados [1]. Se compone principalmente por la cáscara de la cebada, las plántulas, parte del pericarpio y otros materiales que no fueron solubilizados o precipitados en los procesos a los que se sometió previamente. Este material representa aproximadamente el 30 % (p/p) del material de partida. Su composición mayoritaria es variable pero generalmente incluye en materia seca hasta 20 % de proteína, 70 % de fibra y 1,2 % de compuestos fenólicos, principalmente flavonoides y ácidos fenólicos [2]. Existe evidencia científica de la capacidad de estos últimos compuestos para exhibir actividad anticarcinogénica, antiinflamatoria y antioxidante [3].

El contenido de humedad del BSG apenas egresa del proceso varía entre 70 y 80 %. Debido a su alto contenido en agua, polisacáridos y proteínas, éste es particularmente susceptible a sufrir degradación microbiana, constituyendo un subproducto altamente contaminante. Actualmente, el BSG se descarta o comercializa como alimento para ganado; sin embargo, podría ser considerado como materia prima para elaboración de alimentos para consumo humano debido no sólo a su alto poder nutritivo, sino también a su naturaleza de grado alimentario.

En el presente trabajo, se caracterizaron extractos de BSG provenientes de la elaboración de cerveza provistos por un fabricante local. Se estudió el efecto del tiempo de secado del BSG sobre la bioactividad de sus extractos obtenidos posteriormente.

2 Materiales y métodos

2.1 Materiales

El BSG, correspondiente al estilo de cerveza "Dorada Pampeana", fue provisto por la cervecería "Tres Hileras", ubicada en la ciudad de Bahía Blanca. Las muestras se recogieron hasta dos horas después de generadas y fueron procesadas inmediatamente.

2.2 Métodos

Deshidratación del BSG. El BSG utilizado contaba con aproximadamente un 76 % de humedad al momento de egresar del proceso de producción de la cerveza. Con el fin de reducirlo y evitar su degradación, se procedió a prensarlo en una prensa neumática a 4 bar para luego finalizar el proceso en una estufa de circulación forzada a 60 ºC. El tiempo necesario para alcanzar peso constante fue de 5 h. Se decidió estudiar el efecto del tiempo de secado evaluando luego los extractos obtenidos a 5 y 20 h de secado.

Obtención de los extractos de BSG. Las muestras deshidratadas fueron pulverizadas y se seleccionó la fracción pasante por tamiz ASTM 14 (1410 μm). Para la extracción se utilizó una relación de sólido a solvente (etanol/agua (60:40, v/v)) de 1:20 (p/v), estableciéndose las siguientes condiciones operativas: 60 ºC – 30 min – agitación magnética. El sólido residual se separó mediante centrifugación a 7000 rpm durante 10 minutos y el sobrenadante se filtró con membrana de nylon de 0,45 μm de tamaño de poro.

Caracterización de los extractos de BSG. Los extractos fueron caracterizados en cuanto a su bioactividad de acuerdo con la siguiente metodología:
Contenido total de compuestos fenólicos (TPC). La determinación del TPC se realizó según el método colorimétrico de Folin-Ciocalteu siguiendo la metodología reportada por Pacheco et al. [4]. Los resultados fueron expresados como mg de equivalentes de ácido gálico por kg de sólido seco (mg GAE/kg ss).
Poder reductor de iones férricos (FRAP). Se aplicó el método de FRAP, según Pacheco et al. [4]. Los resultados se expresaron en mmol Trolox/kg sólido seco.

Actividad antirradicalaria (AAR, método de decoloración de $ABTS^{+\bullet}$): Se preparó una solución de $ABTS^{+}$ 7 mM y persulfato de potasio 2,45 mM (1:1), mantenida a temperatura de refrigeración y al abrigo de la luz durante 12 h, condiciones necesarias para la formación del radical catiónico $ABTS^{+\bullet}$. Antes de iniciar el ensayo, se realizó una dilución de la solución de $ABTS^{+\bullet}$ en etanol, hasta alcanzar una absorbancia de 0,7. Se mezcló 1 ml de la solución con 10 µl de alícuota de extracto para leer la absorbancia a 734 nm a los 10 min. Los resultados se expresan como %AAR, definida como:

$$\% AAR = \left(1 - \frac{A_{10\,min}}{A_0}\right) 100\,\% \quad (1)$$

A_0: absorbancia antes del agregado de la alícuota.
$A_{10\,min}$: absorbancia a tiempo 10 min.

3 Resultados y discusión

La Fig. 1 muestra los resultados correspondientes al TPC de los extractos obtenidos por secado del BSG por 5 y 20 h. Se puede observar que la extensión del tiempo de secado produce extractos con menor calidad desde el punto de vista de su bioactividad. La disminución en TPC entre 5 y 20h fue de aproximadamente un 15 % en base seca. Esto puede deberse a una degradación de compuestos fenólicos en las muestras deshidratadas de BSG y/o podría ser causado por un cambio físico en las muestras deshidratadas que disminuya la eficiencia de extracción de los mencionados compuestos bioactivos.

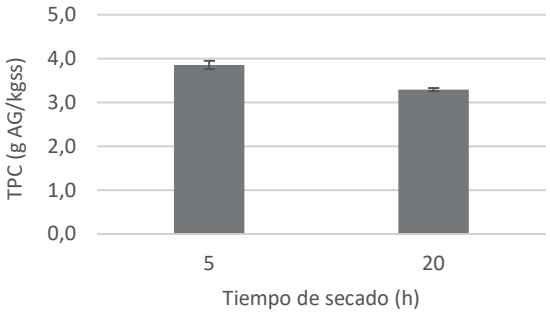

Fig. 1. Contenido de fenoles totales de extractos obtenidos a partir de BSG secado a 5 y 20 h.

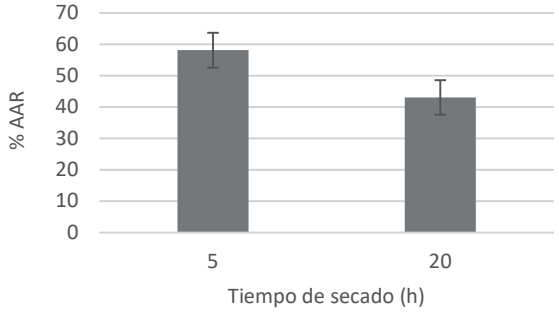

Fig. 2. Actividad antirradicalaria de extractos obtenidos a partir de BSG secado a 5 y 20 h.

Las Fig. 2 y 3 muestran los resultados obtenidos para la AAR y AAO, respectivamente. Al igual que para el caso del contenido de fenoles totales, ambos parámetros de calidad disminuyen al aumentar el tiempo de secado. En el caso de la AAO, esta disminución resultó de aproximadamente un 17 %, mientras que la AAR presentó una caída de alrededor del 26 %. Estas disminuciones se encuentran en concordancia con la menor concentración de compuestos fenólicos en los extractos, los cuales representan los compuestos bioactivos mayoritarios presentes en las muestras [2].

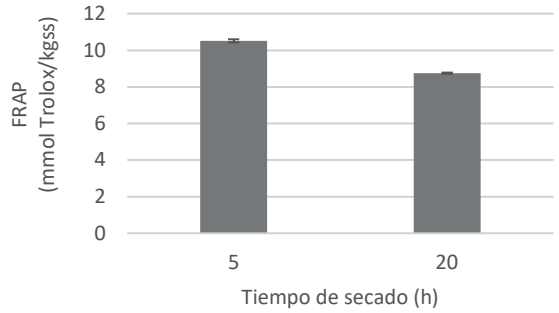

Fig. 3. Poder reductor de iones férricos de extractos obtenidos a partir de BSG secado a 5 y 20 h.

4 Conclusiones

Los resultados obtenidos al evaluar el efecto del tiempo de secado de BSG sobre el contenido de fenoles totales y la capacidad antioxidante y antirradicalaria de los extractos obtenidos mostraron que los tres parámetros de calidad estudiados sufrieron una importante disminución (15 – 26 %) al aumentar el tiempo de secado de 5 a 20 horas.

Estos resultados demuestran la importancia de no extender el tiempo de secado innecesariamente.

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Efecto de la temperatura de secado en la microencapsulación de antioxidantes naturales

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Resumen. La producción de polvos alimenticios se encuentra en crecimiento debido a la mejorada estabilidad que presentan y su fácil transporte y almacenamiento. Los compuestos antioxidantes presentes en las frutas y verduras pueden ser extraídos y vehiculizados en forma de polvos, lo cual además facilita su consumo. Esta estrategia permite también aprovechar compuestos bioactivos que se encuentran en partes de las plantas que no son habitualmente consumidas. Sin embargo, estos compuestos presentan cierta inestabilidad química fuera de su matriz natural. La microencapsulación es una posible solución para preservar la actividad antioxidante de estas sustancias hasta el momento de ser consumidas.
En el presente trabajo se planteó la microencapsulación de hojas de alcaparra, cáscara, albedo y jugo de naranja, obteniéndose un producto particulado rico en bioflavonoides -rutina, hesperidina y narirutina- y vitamina C. El proceso se llevó a cabo mediante secado por atomización utilizando maltodextrina como agente encapsulante. La temperatura de entrada del gas de secado se varió entre 130 y 150 ºC. Los polvos obtenidos fueron caracterizados determinando contenido de flavonoides individuales, vitamina C, fenoles totales, actividad antirradicalaria e higroscopicidad. Asimismo, la performance del proceso se evaluó calculando el rendimiento para cada ensayo. Los resultados obtenidos permitieron concluir que la temperatura de entrada del gas de secado afecta significativa únicamente la higroscopicidad del producto final, encontrándose el mínimo valor de este parámetro para 130 ºC.

Palabras clave: Microencapsulación, Antioxidantes naturales, Residuos agroindustriales.

1 Introducción

La naranja es un fruto rico en ácido ascórbico, narirutina y hesperidina, compuestos con reconocido efecto antioxidante. La hesperidina se encuentra en alta concentración en el albedo -la parte blanca de la cáscara-, mientras que el ácido ascórbico y la narirutina,

se encuentran concentrados en su jugo. Al utilizar la naranja como fuente de estas sustancias se aprovecha la fruta casi en su totalidad, disminuyendo así la generación de residuos. Sólo alrededor de un tercio de las frutas cítricas se utilizan para producir jugo fresco o bebidas a base de cítricos. Por lo tanto, estos alimentos no son debidamente aprovechados en la industria. Sus residuos (cáscaras) tienen valor bajo o nulo e incluso pueden constituir un problema ambiental debido a su acumulación cerca de las zonas industriales. Una posible forma de valorizar las cáscaras y semillas de cítricos, subproductos de la industria, es utilizarlas como fuentes de antioxidantes naturales [1].

Por otro lado, las hojas de alcaparra son una buena fuente de rutina confiriendo valor agregado a este residuo generado en las prácticas agrícolas. La rutina, también conocida como vitamina P, es un compuesto fenólico vegetal muy importante debido a su actividad antioxidante, antiinflamatoria y anticancerígena, y a su capacidad para reducir la fragilidad de los vasos sanguíneos [2].

Resulta interesante desarrollar fórmulas ricas en dichas sustancias, ya que los bioflavonoides (como rutina y hesperidina) son antioxidantes que presentan sinergismo con el ácido ascórbico [3], favoreciendo la asimilación de este último [4].

Otra característica de los antioxidantes es que son fácilmente degradables debido a su sensibilidad a factores ambientales como la luz, el calor, la humedad y el oxígeno [5], por lo que deben ser protegidos para preservar su bioactividad. La microencapsulación se presenta como una solución factible a este problema. En particular, el secado por atomización (spray drying) es un proceso que produce partículas de alta calidad y estabilidad, siendo relativamente flexible, de bajo costo y de operación continua y, por lo tanto, el método de encapsulación más utilizado en la industria alimentaria actualmente [6, 7, 8].

En el presente trabajo se propone coencapsular extractos brutos de albedo y cáscara de naranja, hojas de alcaparro y jugo de naranja con maltodextrina (MD) como agente encapsulante mediante secado por atomización. Se estudió el efecto del aumento de la temperatura del gas de secado sobre diferentes parámetros de calidad del proceso (rendimiento) y del producto (higroscopicidad del polvo, contenido de fenoles totales, flavonoides individuales -hesperidina, rutina y narirrutina- y vitamina C y actividad antirradicalaria).

2 Materiales y métodos

2.1 Materiales

El albedo de naranja fue obtenido a partir de naranjas variedad Valencia, teniendo especial cuidado en eliminar todo resto de flavedo y pulpa que pudiera haber quedado adherida al albedo. Se secó en estufa de circulación forzada a 60 ºC por aproximadamente 4 horas, hasta peso constante. Luego se pulverizó con mortero y se separó la fracción pasante por tamiz ASTM 50 (297 μm). El procedimiento de secado de las hojas de alcaparro fue similar. El jugo de naranja se obtuvo por prensado, para luego ser filtrado con filtro de tela. La MD DE 20 fue gentilmente proporcionada por Ingredion Argentina.

2.2 Métodos

Preparación de las suspensiones a atomizar. En función de determinaciones previas del contenido de flavonoides y ácido ascórbico en los materiales vegetales utilizados, se estableció la siguiente metodología de obtención de los extractos: 0,5:10 (p/v) de hojas secas de alcaparro a mezcla de etanol/agua (70:30, v/v) y 0,05:10 (p/v) de albedo seco a mezcla de etanol/agua (70:30, v/v). El sólido residual luego de la extracción fue separado por filtración con papel de filtro. El solvente orgánico presente en cada uno de los extractos fue evaporado de forma independiente en rotoevaporador. Los extractos fueron congelados hasta su utilización. Los volúmenes de extractos en la suspensión a atomizar fueron los siguientes: 10 mL de extracto concentrado de hojas de alcaparro, 15 mL de extracto concentrado de albedo y 30 mL de jugo de naranja filtrado. Una vez homogeneizados, se agregó un 70 % (p/p sólidos de jugo) de MD. Esta suspensión fue mantenida en continua agitación mientras era alimentada al secadero spray mediante bomba peristáltica.

Coencapsulación de los extractos. La encapsulación se llevó a cabo mediante secado por atomización en un secadero spray (Mini Spray Dryer Büchi B-290). Las condiciones operativas del mismo fueron: caudal de líquido atomizado: 7 mL/min, caudal de aire de atomización: 831 L/h (STP), caudal de gas de secado (nitrógeno): 33 m^3/h. La temperatura de entrada del gas de secado (Tin) se estableció en tres niveles: 130, 140 y 150 ºC.

Cálculo del rendimiento de proceso. Se estimó mediante la Ec. (1). Las masas se determinaron gravimétricamente pesando el producto final colectado en el secadero y considerando el contenido de sólidos de la suspensión atomizada.

$$\text{Rendimiento (\%)} = \left(\frac{\text{masa de sólido recuperado}}{\text{masa de sólido alimentado}}\right) 100\ \% \qquad (1)$$

Caracterización de los polvos obtenidos. Los extractos fueron caracterizados en cuanto a su bioactividad de acuerdo con la siguiente metodología:
Flavonoides individuales. Las soluciones de rutina, narirutina y hesperidina a ser analizadas se obtuvieron tomando 1 g de polvo, agregando 5 mL de agua (para solubilizar la maltodextrina), agitando durante 2 minutos para luego agregar 5 mL de DMSO (con el objetivo de solubilizar completamente los flavonoides) y agitando nuevamente durante 2 minutos. A continuación, se procedió a centrifugar las muestras a 7000 rpm durante 10 minutos. En algunos casos, fue necesario diluir las soluciones con una mezcla DMSO/agua (1:1). Finalmente, se filtró con membrana de PVDF de 0,45 μm de tamaño de poro. La cuantificación se llevó a cabo según Patil y col. [9] en un HPLC (Waters Alliance, e2695) provisto de una columna C18RS y un detector de arreglo de diodos (280 nm para hesperidina y narirrutina y 355 nm para rutina). La fase móvil consistió en un sistema binario de solventes: agua/ácido acético (96:4, v/v, solvente A) y acetonitrilo (solvente B). La elución se estableció en modo gradiente según la siguiente programación: 1) 85 % solvente A por 35 minutos, 2) 50 % solvente A por 5

minutos y 3) 85 % solvente A. El flujo volumétrico se mantuvo en 1 mL/min. La cuantificación se llevó a cabo mediante el método del estándar externo empleando rutina, narirutina y hesperidina comerciales como patrones analíticos. Los resultados se expresaron como mg flavonoide/g polvo.

Contenido total de compuestos fenólicos (TPC). La determinación del TPC se realizó según el método colorimétrico de Folin-Ciocalteu. Brevemente, una alícuota de 100 µL de extracto fue mezclada con 6 mL de agua y 0,5 mL de reactivo de Folin-Ciocalteu en matraz de 10 mL. Luego de 8 minutos, 1,5 mL de una solución al 7,5 % de Na_2CO_3 anhidro se agregó y se llevó a volumen con agua destilada. Se registró la absorbancia a 765 nm luego de 2 horas de incubación en oscuridad. Los resultados fueron expresados como mg de equivalentes de ácido gálico por kg de sólido seco (mg GAE/kg ss) haciendo uso de una curva de calibración construida previamente con ácido gálico como estándar de referencia.

Actividad antirradicalaria (AAR, método de decoloración de DPPH•): La medición de la AAR se determinó agregando una alícuota de los extractos conteniendo los antioxidantes a 3 mL de una solución de DPPH• con absorbancia de aproximadamente 1. Inmediatamente, se comenzó a medir la absorbancia a 517 nm en ciclos de 30 segundos durante 10 minutos, de manera de obtener el valor de absorbancia a tiempo infinito mediante extrapolación matemática. Este valor, junto con el de absorbancia a tiempo inicial, permite el cálculo del porcentaje de actividad antirradicalaria, según Ec. 1.

$$\% \, AAR = \left(1 - \frac{A_{10\,min}}{A_0}\right) 100\,\% \qquad (2)$$

A_0: absorbancia antes del agregado de la alícuota (aproximadamente 1,000).

$A_{10\,min}$: absorbancia transcurridos 10 min del agregado de la alícuota.

Determinación del contenido de vitamina C (VCC). La solución a ser analizada se obtuvo tomando 1 g de polvo, agregando 10 mL de una solución de ácido metafosfórico al 2 % [10], agitando durante 5 minutos para luego centrifugar la suspensión a 7000 rpm durante 10 minutos, para separar los compuestos insolubles en agua. Se procedió a realizar una dilución 1:1 con una solución acuosa de ácido sulfúrico pH 2,5 y luego se filtró con membrana de PVDF de 0,45 µm de tamaño de poro. Brevemente, la técnica de cuantificación se realizó en un HPLC (Waters Alliance, e2695) provisto de una columna C18RS y un detector de arreglo de diodos (254 nm). La fase móvil que se utilizó fue una solución acuosa de ácido sulfúrico pH 2,5. El compuesto de referencia que se utilizó para la construcción de las curvas de calibración fue ácido ascórbico puro (Saporiti), expresándose los resultados como mg AA/g polvo.

Higroscopicidad. Las muestras (1 g) fueron expuestas a una atmósfera de 75 % HR (sol. saturada de NaCl) a 25 ºC durante una semana. La higroscopicidad se calculó según la Ec. (2).

$$\text{Higroscopicidad (\%)} = \left(\frac{\text{masa de agua ganada}}{\text{masa de sólido seco}}\right) 100\,\% \qquad (2)$$

3 Resultados y discusión

En la Fig. 1 se muestra la dependencia del rendimiento del proceso con la temperatura de entrada del gas de secado. Se puede observar que se obtienen rendimientos muy buenos y similares para las tres temperaturas estudiadas.

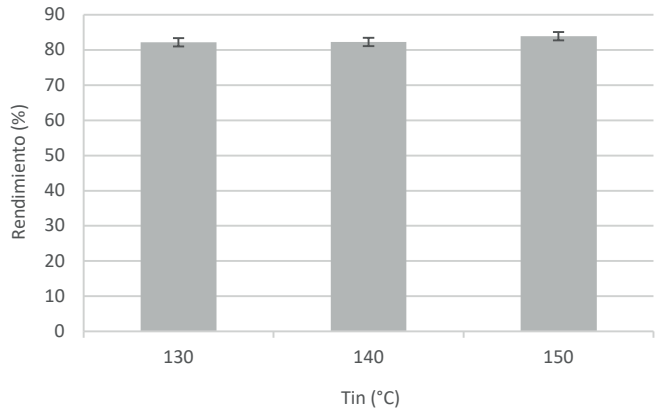

Fig. 1. Rendimiento del proceso de encapsulación en función de la temperatura de entrada del gas de secado.

La higroscopicidad (Fig. 2) muestra cierta dependencia con la temperatura de entrada del gas de secado. En este caso, este parámetro aumenta con dicha variable operativa. La higroscopicidad del polvo afecta negativamente sus propiedades de flujo y su estabilidad química; por lo tanto, se busca que ésta sea mínima, condición que se cumpliría para una temperatura de 130 ºC.

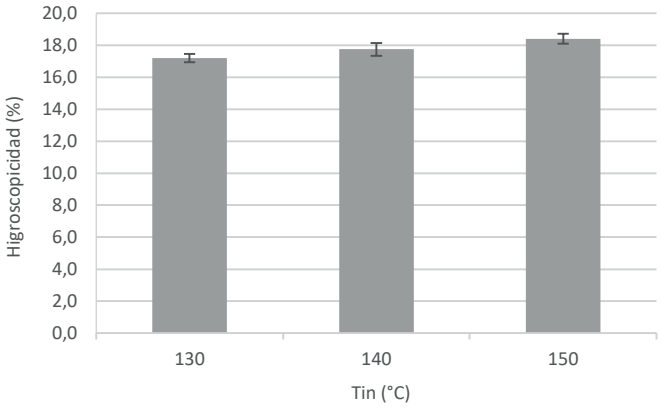

Fig. 2. Higroscopicidad de los polvos en función de la temperatura de entrada del gas de secado.

Respecto al contenido de compuestos bioactivos en los polvos obtenidos, los resultados del contenido total de compuestos fenólicos (TPC) se muestran en la Fig. 3.

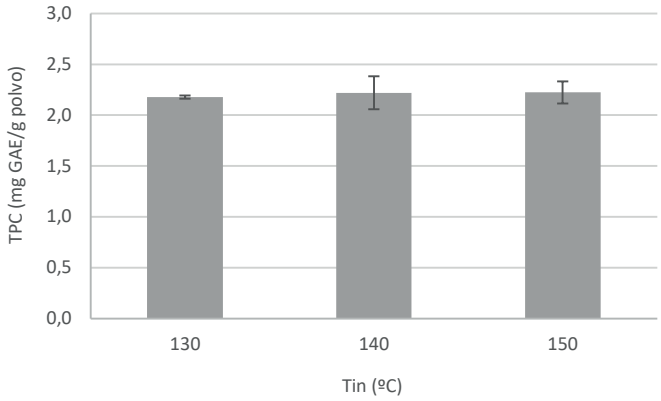

Fig. 3. Contenido total de compuestos fenólicos en función de la temperatura de entrada del gas de secado.

Se obtuvieron valores de aproximadamente 2,2 mg GAE/g polvo para las tres temperaturas de entrada del gas de secado, no encontrándose diferencias significativas entre los valores obtenidos.

En la Fig. 4 se muestran los resultados correspondientes a la actividad antirradicalaria de los polvos obtenidos.

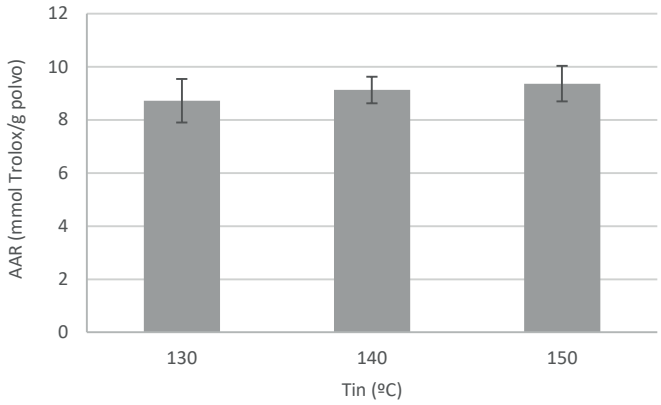

Fig. 4. Actividad antirradicalaria en función de la temperatura de entrada del gas de secado.

Al igual que para el TPC, se encontró que la AAR de los polvos obtenidos a las tres Tin estudiadas fue similar, concluyéndose que resultaría indistinto establecer la temperatura de entrada del gas de secado en cualquiera de los tres valores estudiados.

Finalmente, en la Fig. 5 y 6 se muestran los resultados para el contenido de los flavonoides individuales y de la vitamina C, respectivamente.

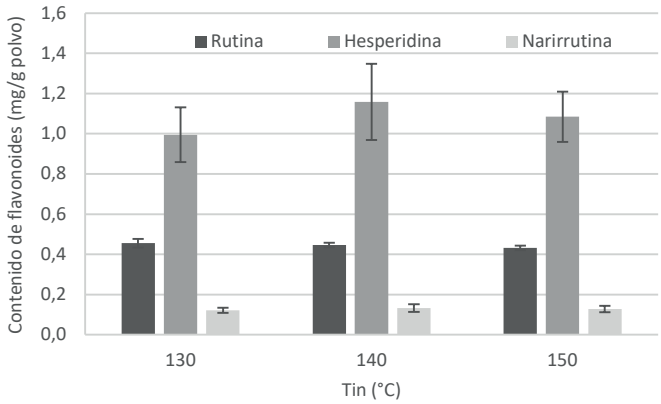

Fig. 5. Contenido de flavonoides individuales en función de la temperatura de entrada del gas de secado.

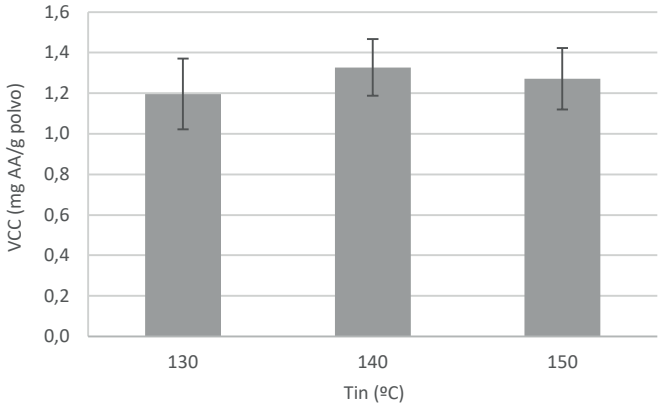

Fig. 6. Contenido de vitamina C en función de la temperatura de entrada del gas de secado.

Observando los valores obtenidos para el contenido de flavonoides individuales, la hesperidina resultó el predominante. Esto se debe a que el mismo está presente no sólo en el albedo de la naranja, sino también en su jugo. En el caso de la narirutina, ésta se encuentra presente principalmente en el jugo de este fruto, aunque en menor

concentración que la hesperidina. Evaluando el efecto de la temperatura de entrada del gas de secado sobre la concentración de estos compuestos en los polvos obtenidos, es posible concluir que no existe diferencia significativa entre los valores obtenidos. Este resultado está en concordancia con el obtenido para el TPC, si se considera que los compuestos fenólicos predominantes en el producto son los flavonoides individuales evaluados.

Respecto al contenido de vitamina C en los polvos, los valores encontrados fluctuaron entre 1,2 y 1,33 mg AA/g polvo, no encontrándose diferencias significativas para las distintas muestras analizadas.

La vitamina C resulta mucho más termolábil que los compuestos fenólicos de alto peso molecular, como la rutina, narirutina y hesperidina. Sin embargo, la primera no se ve afectada por el incremento de la temperatura del gas de secado. Anandharamakrishnan y col. [11] aseguran que las partículas permanecen a su temperatura de bulbo húmedo durante el proceso de evaporación del solvente, evitando que las mismas alcancen la temperatura del gas, protegiendo así los compuestos termolábiles. Por otro lado, el uso de nitrógeno (un gas inerte) en lugar de oxígeno, seguramente colabora en la estabilización de la vitamina.

4 Conclusiones

Se analizaron diferentes parámetros de calidad de proceso y del producto obtenido al manipular la temperatura de entrada del gas de secado durante el proceso de microencapsulación. Los resultados obtenidos permitieron inferir que el único parámetro que se vio afectado por la temperatura de entrada del gas de secado (en el rango estudiado) fue la higroscopicidad del polvo obtenido. Ésta resultó mínima para la menor temperatura evaluada. Como se mencionó anteriormente, es deseable que ésta tome valores lo más bajo posibles debido a que el aumento en el contenido de humedad del polvo durante su almacenamiento se relaciona con problemas en su flujo, dificultando su manipulación, además de acelerar las reacciones degradativas de los compuestos bioactivos contenidos en el producto.

Por este motivo, y dado que los restantes parámetros estudiados no presentaron dependencia con la temperatura de entrada del gas de secado, se recomienda 130 ºC como temperatura óptima de secado, dentro del rango estudiado.

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Estudio cinético de parámetros de calidad nutricional y sensorial en leche tratada térmicamente

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Resumen. En este trabajo se estudiaron las cinéticas de degradación térmica del color, vitamina C y proteínas en leche para un rango de temperaturas de 70 a 100°C. El color fue cuantificado midiendo los parámetros colorimétricos CIELAB, con un colorímetro Kónica-Minolta CR400 (Japón), y determinado a partir de ellos el índice de Pardeamiento (*BI*) y cambio total de color (ΔE). La vitamina C fue determinada por HPLC, mientras que para la cuantificación de las proteínas séricas se utilizó la técnica de Bradford. Todos los parámetros estudiados siguieron una cinética de primer orden, a excepción del cambio de color, que siguió una cinética de orden cero. En todos los casos, la dependencia de la constante de velocidad (*K*) con la temperatura fue modelada mediante la Ecuación de Arrhenius, obteniéndose energías de activación de 148,09, 138,57, 13,04 y 60,03 kJ/mol para *BI,* ΔE*,* vitamina C y proteínas, respectivamente. Las energías de activación revelaron que *BI* es el parámetro más sensible a los cambios de temperatura, mientras que los valores de las constantes de velocidad (*K*) mostraron que la desnaturalización térmica de proteínas presentó la mayor velocidad de degradación en comparación con los demás parámetros estudiados.

Palabras clave: Estabilidad Térmica, Color, Vitamina C, Proteínas, Leche.

1 Introducción

La leche es un alimento de alto valor nutricional debido a su contenido de proteínas, grasas, vitaminas y minerales, necesarias para la nutrición humana [1]. Su compleja composición bioquímica junto con su pH y su alta actividad de agua hacen de ella un medio ideal para el crecimiento microbiano. Debido a esto, es necesario el tratamiento térmico de la leche cruda, siendo la pasteurización por calor uno de los procesos más utilizados para obtener un producto apto para el consumo humano y, por consiguiente, asegurar la inocuidad microbiológica y prolongar la vida útil de este alimento. En la

industria, tanto a nivel mundial como nacional, dicho proceso se lleva a cabo mayormente a través de sistemas continuos de calentamiento, empleando intercambiadores de calor tubulares o de placas [2]. Sin embargo, este procesamiento origina alteraciones en los componentes nutricionales de la leche, principalmente en aquellos componentes termosensibles como lo son las proteínas y las vitaminas hidrosolubles, y sensoriales, al producirse cambios en el color y sabor debido principalmente a reacciones de Maillard [3]. En este sentido, el objetivo del presente trabajo reside en desarrollar cinéticas de degradación térmica de dichos componentes de calidad en leche de vaca, considerando condiciones de tiempo y temperatura requeridas para la pasteurización de este tipo de producto. Dichas cinéticas serán de utilidad para predecir el efecto del procesamiento térmico en las características de la leche y, por consiguiente, para optimizar las condiciones de tratamiento y obtener, con ello, un producto de alta calidad.

2 Materiales y métodos

2.1 Muestras de leche

Para la realización de los ensayos experimentales se utilizó leche fresca entera provista por la Escuela Superior Integral de Lechería (ESIL) y por la Estancia YUCAT, ambas de la ciudad de Villa María, Provincia de Córdoba. Para la determinación de proteínas y ácido ascórbico, se requirió de leche descremada, proceso llevado a cabo por una desnatadora de escala laboratorio. Las muestras fueron almacenadas a 4°C.

2.2 Tratamiento térmico

Para el desarrollo de los estudios cinéticos, muestras de leche fueron colocadas en tubos de vidrio con tapa a rosca de 6 mL y calentadas por inmersión en un baño de agua termostatizado, manteniendo constante la temperatura requerida. Para el estudio de los diferentes parámetros nutricionales y sensoriales se utilizaron temperaturas y tiempos de calentamientos diferentes, lo cual se debe principalmente a las diferencias en las velocidades de formación o degradación de los componentes analizados: compuestos coloreados, vitamina C y proteínas séricas. Para el estudio de parámetros colorimétricos, se utilizó un rango de temperatura entre 80 y 100 °C y tiempos entre 0 y 120 min, para la degradación térmica de la vitamina C, temperaturas entre 70 y 100 °C y tiempos de entre 0 y 33 minutos, mientras que para la desnaturalización de proteínas séricas se realizaron experiencias entre los 70 y 100 °C y tiempos entre 0 y 3 minutos. Al finalizar el tratamiento térmico, las muestras fueron enfriadas rápidamente en un baño de agua-hielo, de manera de detener las reacciones de desnaturalización y degradación que tienen lugar durante el calentamiento.

2.3 Determinación de parámetros colorimétricos

Las muestras de leche tratadas térmicamente se homogeneizaron utilizando un vortex y se colocaron en un recipiente de cerámica de 3 cm de diámetro para realizar la medición de los parámetros colorimétricos. Dichos parámetros se basan en el espacio de color CIELAB compuesto por tres coordenadas colorimétricas, L *, a * y b *. El valor de L * representa luminosidad del color (L*=0 significa negro y L*=100 indica blanco), el valor a * indica su posición entre rojo y verde (valores negativos indican verde mientras valores positivos indican rojo) y el valor b * representa su posición entre amarillo y azul (valores negativos indican azul y valores positivos indican amarillo).

El instrumento utilizado fue un colorímetro Kónica-Minolta CR400 (Japón) y se calibró con una placa blanca estándar (sY = 93,2, sx = 0,3133 y sy = 0,3192). Con las coordenadas colorimétricas obtenidas se determinaron el índice de pardeamiento (BI) (Ecuación 1) y el cambio de color (ΔE) (Ecuación 3) y su variación en el tiempo.

$$BI = \frac{100\,(X-0{,}31\,)}{0{,}17} \tag{1}$$

donde X está definido como:

$$X = \frac{a^* + (1{,}75\,L^*)}{(5{,}645\,L^*) + a^* - (3{,}012\,b^*)} \tag{2}$$

$$\Delta E = \sqrt{(L^* - L_o^*)^2 + (a^* - a_o^*)^2 + (b^* - b_o^*)^2} \tag{3}$$

donde L_o, a_o y b_o son las coordenadas CIELAB de la leche en tiempo cero. Para desarrollar la cinética de cambio de color, el tratamiento térmico y el análisis de las muestras se llevaron a cabo por triplicado.

2.4 Contenido de vitamina C

La vitamina C se cuantificó por HPLC (High Performance Liquid Chromatography) teniendo en cuenta los trabajos de Chotyakul et al. [4] y Tiwari et al. [5] con adaptaciones. Se colocaron 4 mL de leche en un tubo de plástico y se realizó la extracción con 1 mL de ácido metafosfórico al 2,5 % (p/v). Los tubos se cubrieron con papel aluminio de manera de proteger las muestras de la luz, y evitar la oxidación de la vitamina. Luego, la mezcla se homogenizó en un vortex por 20 s y se centrifugó a alta velocidad y baja temperatura (10000 rpm y 4 °C) durante 10 min. Se colocó 1 mL del sobrenadante obtenido anteriormente en un eppendorf de 1 mL protegido de la luz, previamente filtrado utilizando un filtro de 45 µm. Por último, se inyectó 20 µL del sobrenadante filtrado en el equipo de HPLC.

El sistema cromatográfico utilizado consistió en un HPLC (Thermo Scientific ULTIMATE 3000, EE. UU.) con una columna C18. Se usó un detector DAD a una longitud de onda de 243 nm. La fase móvil consistió en una mezcla de 0,5% (p/v) de ácido metafosfórico con acetonitrilo (ACN) (pH:2) en relación fase acuosa – acetonitrilo 99:1. La misma fue bombeada a un caudal de 0,5 mL/min. Los resultados se calcularon utilizando la curva estándar de vitamina C y las áreas obtenidas en los

cromatogramas. Las determinaciones se realizaron por triplicado en las muestras obtenidas a los diferentes tiempos en un tratamiento térmico.

2.5 Determinación de proteínas

Para la determinación de proteínas en leche tratada térmicamente, las muestras se centrifugaron a 4°C, 10000 rpm y 30 minutos para producir la sedimentación de las proteínas desnaturalizadas, realizándose luego la determinación de las proteínas presentes en el sobrenadante con la técnica propuesta por Bradford [6] con ligeras modificaciones y utilizando albúmina de suero bovino (BSA) como estándar. Para ellos, se realizaron diluciones de 1/100 y 1/200 del sobrenadante obtenido en agua destilada. Posteriormente, se colocaron 10 µL de cada dilución en pocillos de una placa de 96 Wells y se añadieron 190 µL del reactivo color Bradford (BioRad) (dilución 1/5 en agua destilada) a cada uno de los pocillos, para leer finalmente las absorbancias a 570 nm en un espectrofotómetro de microplacas Multiskan Go (ThermoFisher Scientific). Las determinaciones se realizaron por duplicado en las muestras obtenidas a los diferentes tiempos en un tratamiento térmico.

2.6 Modelos cinéticos

Las cinéticas de cambio de color, índice de pardeamiento, degradación de vitamina C y desnaturalización de proteínas en leche tratada térmicamente fueron evaluadas teniendo en cuenta los modelos cinéticos de orden cero (Ecuación 4) y de primer orden (Ecuación 5).

$$C = C_o - K.t \tag{4}$$

$$\frac{C}{C_o} = e^{-K.t} \tag{5}$$

donde C es el parámetro a estimar, C_o es el valor del parámetro en el tiempo cero, t es el tiempo de procesamiento térmico y *K* es la constante de velocidad a la temperatura T. Luego de la medición de los parámetros a diferentes tiempos, se graficó C_o-C y C/C_o en función del tiempo para cinéticas orden cero y de primer orden, respectivamente y para cada temperatura. Posteriormente, se realizó el ajuste lineal o exponencial según el orden de reacción ensayado.

La dependencia de la constante de velocidad (*K*) con la temperatura fue modelada mediante la Ecuación de Arrhenius (Ecuación 6).

$$\ln(K) = ln(Kref) - \frac{Ea}{R}\left(\frac{1}{T}\right) \tag{6}$$

donde *Kref* es el factor preexponencial, *Ea* es la energía de activación, *R* es la constante universal de los gases y T es la temperatura absoluta. Los valores de *K,* para cada temperatura y para cada cinética, se obtuvieron de las ecuaciones (4) y (5), por lo que al graficar ln (*K*) vs. 1/T es posible encontrar los demás parámetros de la Ecuación de Arrhenius.

3 Resultados y discusión

3.1 Parámetros colorimétricos

El pardeamiento de la leche, producido durante el tratamiento térmico principalmente por reacciones no enzimáticas o reacciones de Maillard, puede ser considerado un indicador de la severidad del mismo. En la Tabla 1 se presentan los parámetros cinéticos correspondientes al índice de pardeamiento y el cambio de color. El primero siguió una cinética de primer orden (Figura 1) mientras que el segundo mostró una cinética de orden cero (Figura 2), en concordancia con lo encontrado por Pagliarini et al. [7]. Estos autores estudiaron el cambio de color en leche fresca descremada debido a tratamientos térmicos a temperaturas de entre 90 y 130 °C y un rango de tiempo de 0 a 60 minutos, reportando una energía de activación de 101,8 kJ/mol para el cambio de color. Por otro lado, Rhim et al. [8] evaluaron los parámetros colorimétricos Hunter *L*, *a* y *b* en un amplio rango de temperaturas (entre 100 y 150 °C) y tiempos (0 a 180 minutos), encontrando que el índice de pardeamiento aumentó con la temperatura siguiendo una cinética de orden cero y reportando una energía de activación de 123,5 kJ/mol. Como se puede observar, las energías de activación obtenidas en nuestro estudio para el cambio de color e índice de pardeamiento resultaron mayores a los reportados por Pagliarini et al. [7] y Rhim et al. [8], respectivamente. Lo anterior podría deberse a las diferencias de rangos de temperaturas evaluados en los diferentes trabajos; siendo mayor la Ea, que indica la sensibilidad a los cambios de temperatura, cuando las temperaturas son más bajas.

Como es de esperarse, los valores de *K* aumentaron con la temperatura para ambos parámetros, lo cual revela que a medida que se incrementa la temperatura aumenta la velocidad de aparición de componentes coloreados. Para ambos, la dependencia de la constante de velocidad (*K*) con la temperatura fue modelada mediante la Ecuación de Arrhenius, obteniendo coeficientes de correlación (R^2) de 0,99 y 0,97 para el índice de pardeamiento y cambio de color, respectivamente.

Tabla 1. Parámetros cinéticos de variación de color.

Índice de Pardeamiento					
T(°C)	*K (min^{-1})*	*R^2*	*K_{ref}*	*E_a (kJ/mol)*	*R^2*
80	0,0004	0,9260			
90	0,0014	0,9556	$3{,}13.10^{18}$	148,09	0,99
100	0,0060	0,9950			
Cambio de Color					
80	0,0042	0,9710			
90	0,0104	0,9637	$1{,}17.10^{18}$	138,57	0,97
100	0,0532	0,9898			

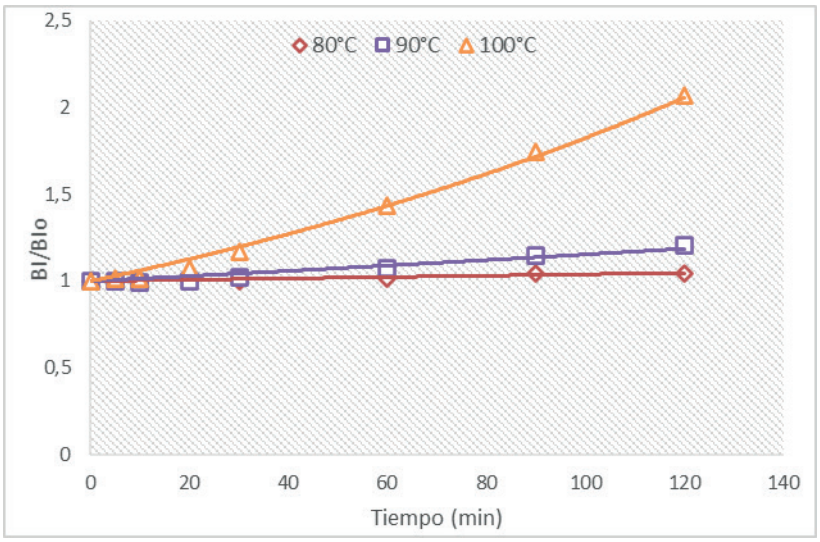

Fig. 1. Cinética de índice de pardeamiento en leche tratada térmicamente a diferentes temperaturas. Las líneas continuas corresponden al modelo ajustado de primer orden.

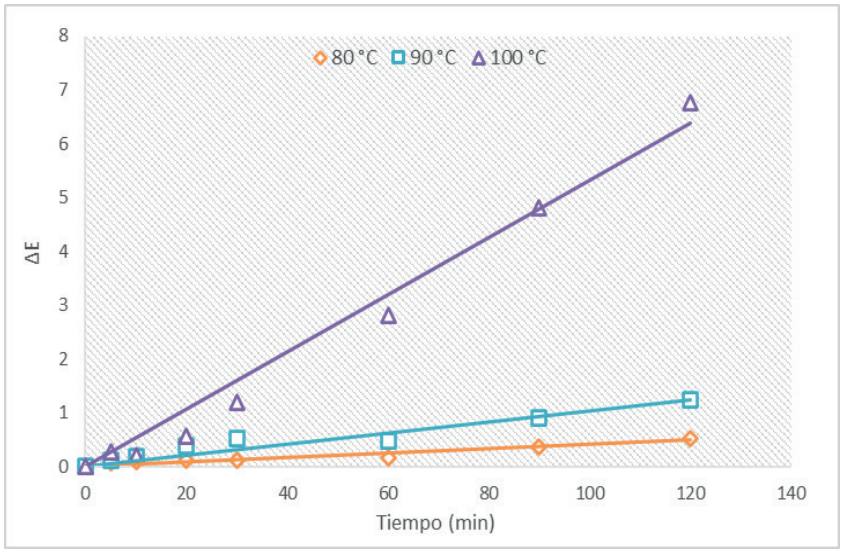

Fig. 2. Cinética de cambio de color en leche tratada térmicamente a diferentes temperaturas. Las líneas continuas corresponden al modelo ajustado de orden cero.

3.2 Degradación de vitamina C

En la Figura 3 se presenta la variación de vitamina C en leche, para diferentes tiempos y temperaturas de procesamiento. En la tabla 2 se presentan los parámetros cinéticos

obtenidos, encontrándose que la degradación térmica de esta vitamina siguió una cinética de primer orden, mientras que la dependencia de la constante de velocidad (*K*) con la temperatura fue modelada mediante la Ecuación de Arrhenius, consiguiendo un muy buen ajuste, con un R^2 de 0,94.

De todas las vitaminas hidrosolubles presentes en la leche, la vitamina C o ácido ascórbico es la más termosensible, reportándose pérdidas de hasta un 40% luego de tratamientos UHT [9]. Si bien son escasos los trabajos de investigación tendientes a evaluar el efecto del procesamiento térmico sobre la vitamina C en leche de vaca, muchos autores han estudiado la degradación térmica del ácido ascórbico en una gran variedad de alimentos durante los tratamientos térmicos y han encontrado que éste sigue una cinética de primer orden [10, 11, 12, 13]. Como se dijo anteriormente, en este estudio, se encontró que la degradación térmica de esta vitamina siguió una cinética de primer orden al igual que lo reportado por Bendicho et al. [9]. Estos autores evaluaron los efectos del tratamiento de campo eléctrico pulsado de alta intensidad (HIPEF) en vitaminas solubles (entre ellas el ácido ascórbico) y liposolubles en leche, comparándolo con los tratamientos térmicos convencionales, para los cuales trabajaron con tiempos de hasta 60 minutos a temperaturas entre 50 y 90 ° C. Como resultado, observaron que la retención de ácido ascórbico siguió un modelo cinético de primer orden tanto para HIPEF como para los procesos térmicos convencionales, mientras que la constante de velocidad (*K*) varió entre 9.10^{-3} y 8.10^{-2} min^{-1} para la cinética correspondiente a tratamientos térmicos convencionales. En cuanto a la energía de activación reportada por estos autores, es bastante superior (63,6655 kJ/mol) a la obtenida en el presente estudio, lo cual puede deberse no sólo al tratamiento térmico y las condiciones utilizadas, sino también al agregado de vitaminas, entre ellas ácido ascórbico, a la leche a tratar.

Tabla 2. Parámetros cinéticos de la degradación térmica de vitamina C

T(°C)	*K* (min^{-1})	R^2	K_{ref}	E_a (kJ/mol)	R^2
70	0,0231	0,9813	2,32	13,04	0,94
80	0,0287	0,9909			
90	0,0322	0,9811			
100	0,0342	0,9796			

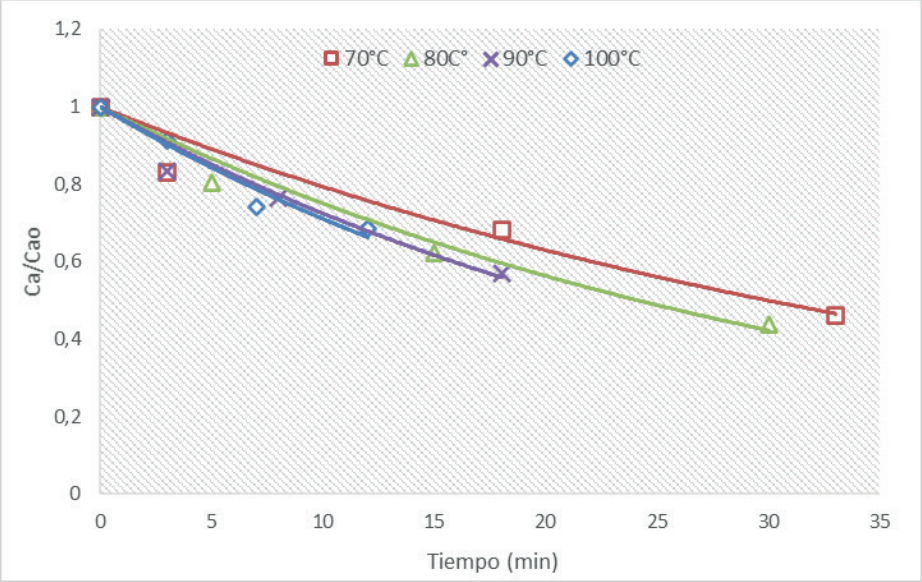

Fig. 3. Cinética de degradación térmica de vitamina C en leche tratada térmicamente a diferentes temperaturas. Las líneas continuas corresponden al modelo ajustado de primer orden.

3.3 Desnaturalización de proteínas

En la figura 4 se presentan las cinéticas de desnaturalización de proteínas de la leche debida a los tratamientos térmicos, a diferentes temperaturas. El tiempo necesario para alcanzar la temperatura de tratamiento fue inferior a 30 segundos, razón por la cual este período de tiempo se excluyó del análisis de los parámetros cinéticos. Los tratamientos térmicos de la leche tienen un gran efecto sobre la estructura y las propiedades de las proteínas del suero, siendo las principales proteínas séricas la β-LG y la α-LA, que representan el 50 y el 20% del total, respectivamente [14]. Un tratamiento térmico mayor a 60 °C da como resultado la desnaturalización de las proteínas del suero, proceso complejo que consiste en el despliegue de las moléculas de proteína, seguido inmediatamente por reacciones de agregación irreversibles [15]. Una gran cantidad de autores han realizado el estudio de las cinéticas de desnaturalización de estas proteínas, en leches con diferentes porcentajes de materia grasa, diferentes tratamientos térmicos con diferentes condiciones de tiempo-temperatura y métodos de determinación [14, 15, 16, 17, 18, 19, 20]. En dichos trabajos, encontraron que entre los factores que influyen en el grado de desnaturalización de las proteínas del suero, se encuentran las condiciones de calentamiento y sistemas de tratamiento térmico y el método de determinación de la desnaturalización de la proteína de suero [15]. Adicionalmente, han reportado que la cinética de desnaturalización de la α-LA es de primer orden, mientras que la de la β-LG puede seguir una cinética de orden 1, 2 o 1,5, dependiendo del autor. Sin embargo, la mayoría de los trabajos coinciden en que estas cinéticas son lineales en dos rangos

de temperaturas: entre 70 y 95 °C, en la cual se obtienen altas energías de activación y entre 95 °C y 140 °C, con bajas energías de activación.

En nuestro estudio se encontró que la desnaturalización de las proteínas séricas, entre 70 y 100 °C, siguió una cinética de primer orden (Figura 4), mientras que la dependencia de la constante de velocidad *(K)* con la temperatura fue modelada mediante la Ecuación de Arrhenius. Los parámetros cinéticos obtenidos se muestran en la tabla 3, reportándose un valor de energía de activación menor que el encontrado en la literatura para el rango de temperaturas estudiado, lo cual puede deberse fundamentalmente al sistema de calentamiento empleado y el método analítico utilizado para la determinación del grado de desnaturalización.

Tabla 3. Parámetros cinéticos de desnaturalización de proteínas séricas.

T(°C)	*K (min^{-1})*	*R^2*	*K_{ref}*	*E_a (kJ/mol)*	*R^2*
70	0,0932	0,9748	1,46.10^8	60,03	0,96
80	0,2194	0,9735			
90	0,3878	0,9803			
100	0,5006	0,9829			

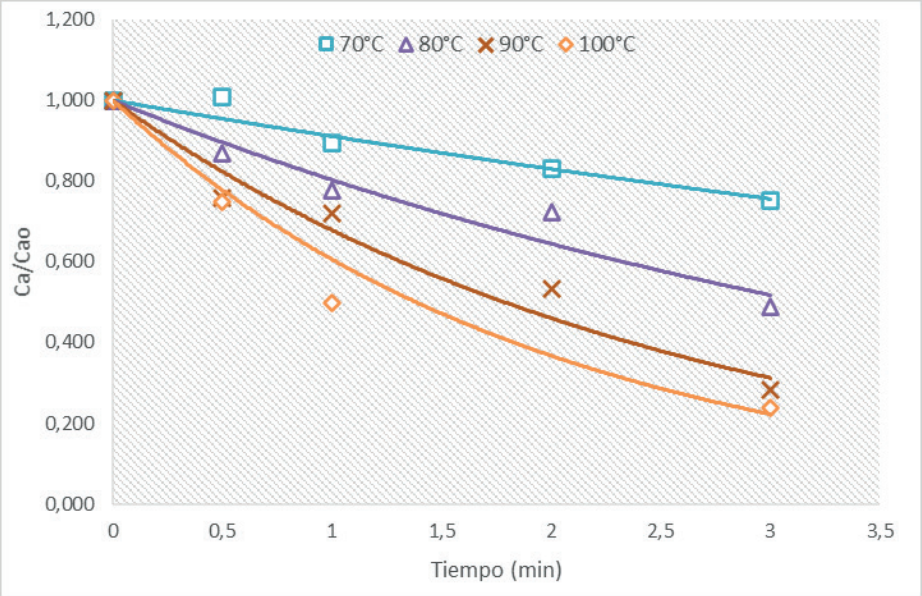

Fig. 4. Cinética de desnaturalización térmica de proteínas séricas en leche tratada térmicamente a diferentes temperaturas. Las líneas continuas corresponden al modelo ajustado de primer orden.

4 Conclusiones

Este trabajo tuvo como objetivo determinar la cinética de la degradación térmica de componentes nutricionales como la vitamina C y las proteínas séricas y de componentes sensoriales como el índice de pardeamiento y cambio de color. El modelo cinético de primer orden fue el más adecuado para las cinéticas analizadas, con excepción del cambio de color, el cual siguió una cinética de orden cero. Las variaciones de las constantes de velocidad con la temperatura fueron consistentes con la relación de Arrhenius. Al observar los resultados de los parámetros cinéticos, se puede concluir que las energías de activación revelaron que el índice de pardeamiento es el parámetro más sensible a los cambios de temperatura, mientras que los valores de las constantes de velocidad (K) mostraron que la desnaturalización térmica de proteínas séricas presentó la mayor velocidad de degradación en comparación con los demás parámetros estudiados. Los resultados obtenidos en este trabajo podrían ser útiles para optimizar el proceso de pasteurización de la leche, a fin de minimizar el pardeamiento y la pérdida de componentes nutricionales, a través de acoplar dichas cinéticas a modelos de transferencia de calor usando herramientas de simulación computacional

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Nanostructured lipid carrier developed with propolis wax residues

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1 Introduction

Propolis is widely used in food and pharmaceutical industries because of their antioxidant and antimicrobial activity [1]. When the content of propolis wax is major than 40%, which is the maximum limit established by the Argentine legislation, raw propolis is considered as low quality and usually discarded [2]. However, propolis wax also has plenty of properties to be exploited in several fields of science and technology. Propolis wax exhibits similar composition and physicochemical properties to bee wax, is stable over time, solid at room temperature, insoluble in water, resistant to hydrolysis, and natural oxidization [3]. Due to its polyphenols content, about 2.4-5%, propolis wax also has antioxidant and antimicrobial activity [4].

Quercetin (3,3′,4′,5,7-pentahydroxyflavone) is a potent antioxidant flavonoid well known because of its health benefits as a neuroprotective, antioxidant, antiviral, anticancer agent, antihypertensive, vasodilator, anti-inflammatory, and anti-allergy [5]. Therefore, quercetin has been used as a nutritional supplement or added to food and beverages. However, the limitation of quercetin incorporation into foods is its degradation when it is exposed to high temperature, oxygen or light, and its poor solubility [6].

Lipid-based nanocarriers, such as nanostructured lipid carriers (NLCs) are solid lipid nanoparticles composed of a mixture of solid and liquid lipids, used as a nutritional supplement carrier in the food industry [7]. NLCs have the advantage to be loaded with hydrophilic or hydrophobic compounds with high loading capacity and a minimized expulsion during storage [8]. Thus, the incorporation into NLCs of poor water-soluble bioactive compounds such as oil-soluble vitamins, carotenoids or flavonoids, increases their stability and bioavailability in foods [9].

The uses of natural biomaterials were studied in the last years for lipid-based nanocarriers development. The aim of this work is to develop quercetin loaded NLCs from propolis wax residues, in order to improve the bioavailability and stability of quercetin into foods. Furthermore, it is worth mentioning that this add value to low quality propolis with high wax content.

2 Material and methods

Raw propolis samples were harvested from Río Negro province, Argentina. Propolis physicochemical characterization was carried out according to the Argentine regulation IRAM-INTA 15935-1: 2008 [2]. Propolis wax was extracted from propolis by Soxhlet extraction method using hexane as solvent. The traces of solvent remaining were removed with a nitrogen stream up to constant weight. The wax melting point and crystallization profile were determined by differential scanning calorimetry (DSC).

For NLCs preparation, the lipid phase was composed of propolis wax (PW) and as cosurfactant high oleic sunflower oil (SO) and soy lecithin (SL). Surfactant Tween 80 (T80) and ultra-pure water (W) were used for the aqueous phase composition. Quercetin (Q) was used for NLCs loaded. The proportions of the aqueous and lipid phase were previously optimized by a Simplex Lattice multicomponent mixtures experimental design. The optimized NLCs were synthetized in two successive steps. First, the lipid phase was prepared by melting 4.20% (w/w) PW, 1.80% (w/w) SO, 2.30% (w/w) SL and different Q proportions (from 8.5 to 200 mg) at 80 ± 5 °C. On the other hand, the aqueous phase was prepared with 6.20% (w/w) T80 and 85.5% (w/w) W at 80 ± 5 °C. The emulsion was performed by slowly dropped the aqueous phase on the lipid once, under constant stirring conditions at 500 rpm with a magnetic bar. Then, the pre-emulsion was obtained by homogenizing for 5 min at 10000 rpm and 80 ± 5 °C using a handheld homogenizer. The obtained pre-emulsion was ultrasonicated for 8 minutes with an ultrasonic homogenizer using a 12.7 mm diameter x 13.65 mm high titanium tip and 10.5 W dissipated ultrasonic power, keeping always the temperature above the wax melting point. Finally, the emulsion was rapidly immersed into an ice bath for 30 minutes to achieve NLCs formation.

The optimized NLCs were characterized by dynamic light scattering (DLS), transmission electron microscopy (TEM), and differential scanning calorimetry (DSC). NLCs entrapment efficiency (EE%) was calculated by determining the unencapsulated quercetin amount after a centrifugation step, using UV-Vis spectrometric [10]. The NLCs structure and stability were studied by multiple light scattering (MLS). Since emulsions were opaque, only the backscattering (BS) detector was used for data collection until 40 days approximately (≈1.000 hours).

The results were analyzed through a two-way ANOVA and LSD Fisher test and Bonferroni tests were used for comparison of means ($\alpha = 0.05$) with the statistical analysis software InfoStat (Version 2018, Grupo InfoStat, FCA, National University of Cordoba, Argentina).

3 Results and discussion

3.1 Raw propolis and propolis wax characterization

The physicochemical composition analysis of raw propolis is important in ordered to determine the quality of this material for industrial uses. The physicochemical requirements established by the Argentine Food Code (Código Alimentario Argentino – CAA) [11] and characterization results for raw propolis are shown in Table 1.

Table 1. Raw propolis characterization.

	* % (w/w)	Values accepted by CAA % (w/w)
Humidity	1.74 ± 0.04	Max 10.0
Wax	26.4 ± 2.82	Max 40.0
Resins	57.4 ± 2.51	Min 30.0
Ashes	2.05 ± 0.03	Max 5.0
Mechanical impurities	9.25 ± 0.39	Max 25.0

*Mean values ± confidence intervals are shown, n = 3.

The PW DSC thermograms presented transition temperatures from 34.9 to 63.7 °C and 60.0 to 38.8 °C, determined from the minima of the endothermic and exothermic transitions, respectively. The enthalpies were obtained by the integration of those using linear baselines. PW melting curve presents at least two composed chemicals, with a higher content on a melting peak at 61.3 °C and enthalpy of 121.5 J g^{-1}. Three crystallization peaks are presented with a maximum one at 59.0 °C and enthalpy of 117.2 J g^{-1}. The presence of several peaks is attributed to the complex composition and heterogeneity of the matrix. It was observed that changes between 40 to 60 °C were due to free acids, hydrocarbons, and fatty acid esters in waxes [12].

3.2 NLCs optimization synthesis

The ultrasound application time was selected based on the smallest particle size obtained. For this, the NLCs Z-average was studied after being exposed to 0, 2, 5, 8, and 10 minutes to the ultrasound probe action. As expected, an abrupt decrease in the NLCs particle size was observed. After 8 and 10 minutes, Z-average sizes were 131.0 ± 0.7 nm and 129.0 ± 2.7 nm, respectively. As there are no significant differences between both ultrasound application times, 8 min of treatment was selected in order to reduce synthesis time. Fisher's least significant difference (LSD) and Bonferroni tests were used for comparison of means ($P \leq 0.01$).

A simplex Lattice mixture experimental design was used to optimize aqueous and lipid phases proportion reagents [13]. Statistical experimental design methods are commonly used to achieve desired properties and establish the optimal proportions of ingredients in a mixture. The design study the interaction between factors and their effects over the response variable. The experimental domain was established selecting

a maximum and minimum value for each factor and setting the necessary restrictions. The levels for all variables were selected based on good results reported in the literature for wax NLCs synthesis [14]. In this work, restrictions were set for lipids proportion (PW and SO) from 6.0 to 10.0% (w/w) and surfactant phase (SL and T80) between 4.0 and 8.0% (w/w). The experimental design conditions for each variable are given in Table 2. A total of twenty-five experiments were carried out and NLCs particle size, determined by DLS, was used as a response. All of them were conducted randomly and the experimental data obtained were analyzed using ANOVA.

Table 2. Experimental design conditions

Level	Propolis wax	High-oleic sunflower oil	Tween 80	Soy lecithin	Water
Low (%)	3.0	1.8	2.9	0.8	83.4
High (%)	7.0	5.0	6.2	2.3	89.4

The fitted surface response obtained can be represented for the following equation:

$$Y\ (nm) = 80.64\ PW + \ 106.21\ SO - \ 77.38\ \ T80 - 92.86\ SL\ \ + 8.34\ W \quad (1)$$

According to eq. (1), the most significant effects were: propolis wax, high-oleic sunflower oil, and water percentages. Furthermore, increments in these parameters provide an increment of NLCs particle size, but an increase in surfactant and cosurfactant proportions cause a decrease in the analytical signal (as evidenced in eq. 1). The estimated model for mixtures is statistically significant, with a P-value < 0.01% and a coefficient of determination $R^2 = 0.952$, indicating a good fit. The NLCs obtained were in the size range between 40.7 ± 0.4 nm to 187.4 ± 1.7 nm. The optimum mixture parameters for smallest NLCs size were 4.20% (w/w) PW, 1.80% (w/w) SO, 6.20% (w/w) T80, 2.30% (w/w) SL and 85.5% (w/w) W.

3.3 NLCs characterization

The particle size of NLCs is considered as the mean hydrodynamic diameter (z-average), and the polydispersity index (PDI) represents the particle size population distribution. Free NLCs particle size was from 44.7 ± 1.3 nm and a PDI of 0.451 ± 0.013. For NLCs quercetin loaded (from 8.5 to 200 mg) size range was from 38.6 ± 0.1 to 77.2 ± 0.1 nm and PDI between 0.439 ± 0.003 and 0.623 ± 0.003. The TEM pictures of free NLCs and quercetin loaded dispersion synthetized under the optimal conditions are presented in Figure 1a). The images confirmed a particles size in the nano-range (~ 50nm), in concordance with the particle size measurements. Also, most NLCs particles appeared with a spherical shape. DSC analysis was used to characterize biological active agents loaded lipids nanocarriers. Also, the thermal analysis can provide detailed information on these loaded nanoparticles about their stability [15]. Figure 1b) shows the DSC thermograms of wax propolis and lyophilized free and 100 mg quercetin loaded NLCs formulation. The enthalpies were obtained by the integration of the

minima endothermic transitions using linear baselines. Developed NLCs presents a low ordered crystalline structure, due to the heterogeneous composition of propolis wax [16]. Free and loaded NLCs shows a broad shallow endothermic peak with a maximum at 61.1 °C and 60.7 °C, respectively. Enthalpy values were 41.7 J g^{-1} for free NLCs and 45.9 J g^{-1} for quercetin loaded NLCs.

For the optimized NLCs formulation loaded with quercetin between 8.5 and 200 mg, entrapment efficiency was from 82.6 to 99.1%, showing the best results when the amount of quercetin added was 150 mg. The use of a Turbiscan optical analyzer is a helpful tool to detect earlier than with naked eyes the instability phenomena. Fig. 2 shows the backscattering data values studied during 40 days of storage. The NLCs Q150 mg formulation resulted to have the lowest BS(%) variation and was considered to be the most stable one. Increments of BS(%) in the middle zone was associated with a particle size increase. Indeed, NLCs Q150 mg shows less than 5% of BS(%) increment during the first 5 days and then the signal was stable for at least the next 30 days.

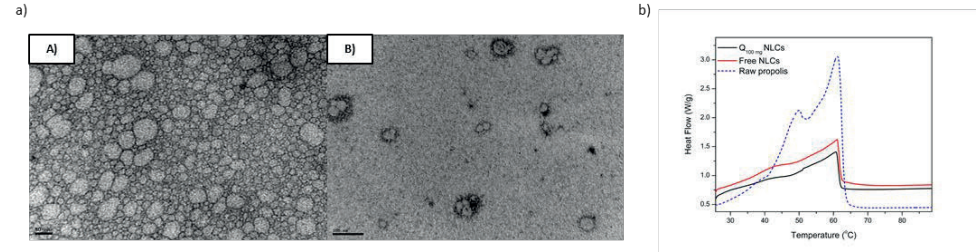

Fig. 1. a) TEM microphotograph of optimum A) free NLCs formulation and B) loaded with quercetin 100 mg and **b)** DSC thermograms of propolis wax, free and loaded NLCs.

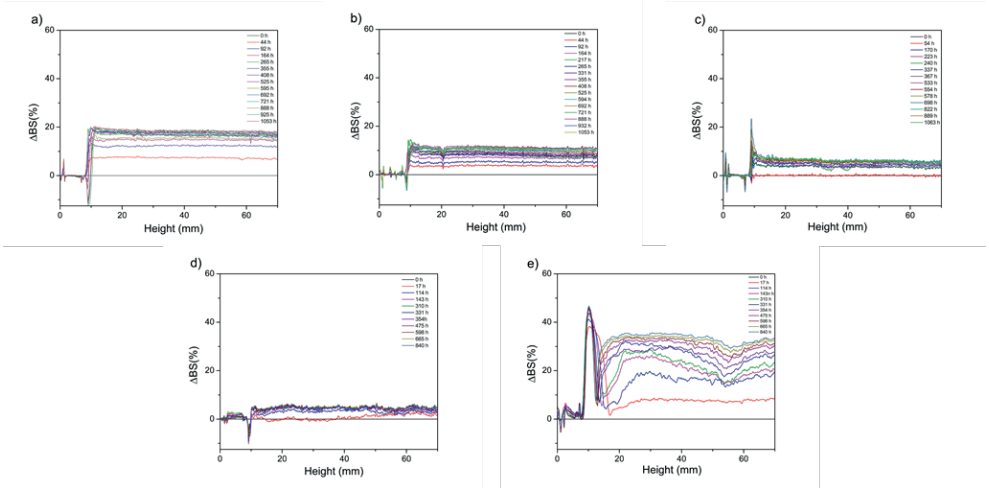

Fig. 2. Delta backscattering (ΔBS) profile as a function of cell height with storage time (samples were stored for 40 days) and photograph (2 h after preparation): **a)** Free NLCs, **b)** NLCs Q8.5mg, **c)** NLCs Q100mg, **d)** NLCs Q150mg and **e)** NLCs Q200mg.

4 Conclusion

The results confirmed that there is possible to obtain a stable NLCs quercetin loaded formulation using propolis wax residues. The reagent proportions in the aqueous and lipid phases were successfully optimized by a simplex lattice mixture experimental design. The optimum mixture parameters were 4.20% (w/w) PW, 1.80% (w/w) SO, 6.20% (w/w) T80, 2.30% (w/w) SL and 85.5% (w/w) W.

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Relationship between microstructure, rheological behavior and kinetic stability of oleogel emulsions produced with recovered and commercial sunflower waxes

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Abstract. Mass fractal dimensions determined by microscopy and rheology were used to characterize the microstructure of oleogels emulsions prepared with recovered and commercial sunflower waxes as structuring agent. The emulsions were prepared using 2, 3.5, and 5% w/w wax in oleogel. Fractal dimension was related to macroscopic behaviors through analysis rheological and long-term kinetic stability of emulsions.

Keywords: Oleogel Emulsions, Sunflower Waxes, Fractal dimension, Rheology.

1 Introduction

Emulsions based on vegetable oil-wax oleogels have shown to be a promising alternative for replacing margarines and solid fats containing a high proportion of saturated and *trans* fatty acids (Hwang, Singh, Winkler-Moser, Bakota, & Liu, 2014; Merchán Sandoval, Carelli, Palla, & Baümler, 2020). Oleogels are systems in which liquid oil is structured into a three-dimensional network by adding one or more gelator molecules. In particular, the sunflower waxes have shown great efficiency to structure several edible oils using low concentrations (Hwang et al., 2014). They are obtained through the oil winterization process and subsequent purification stages. In this work, we are especially interested in elucidating the relationships between microstructure and macroscopic behavior of oleogel-based emulsions prepared using sunflower waxes recovered from filter cake from the winterization process with a simple hexane extraction procedure in comparison with those obtained using commercial sunflower waxes. Mass fractal dimensions determined by microscopy and rheology were used to quantify the microstructure of the studied systems since fractal dimension values are sensitive to the combined effects of crystal size, morphology, and the spatial distribution of mass within the fat crystal network (Tang & Marangoni, 2006). Furthermore, the rheological behavior of the emulsions and their long-term kinetic stability were analyzed.

2 Materials and Methods

2.1 Materials

High oleic sunflower oil (HOSO) was supplied by a local factory. Recovered sunflower waxes (RW) were obtained by processing filter cakes wastes from sunflower oil winterization, as it was described by Merchán et al. (Merchán Sandoval et al., 2020), and commercial sunflower waxes (CW) were provided by Koster Keunen Inc. LLC (Watertown, USA). All reagents were analytical grade unless otherwise stated. Soy lecithin powder, fat-free milk powder, and potassium sorbate were purchased from a local grocery store.

2.2 Preparation of oleogel emulsions

The oleogel emulsions were prepared through simultaneous oleogelation and emulsification from HOSO and waxes (CW or RW) -2, 3.5, and 5% w/w wax in oleogel- and an aqueous solution, following a procedure previously reported (Merchán Sandoval et al., 2020). The resulting emulsions were put into cylindrical containers and cooled at 5 °C for 24 h, allowing semisolid materials to be obtained. The emulsions were coded according to the type of wax and their concentration in the oleogel as CW2, CW3.5, CW5, RW2, RW3.5, and RW5.

2.3 Characterization of oleogel emulsions

Microstructural analysis from images. A small amount of oleogel emulsion sample was placed between a slide and a cover slide. After that, sample micrographs were obtained by a polarized light optical microscope (Carl Zeiss AG, Germany) with a 160x objective lens equipped with a digital camera.

The box-counting fractal dimension (Dbc) was determined following the methodology described by Palla et al. (Palla, de Vicente, Carrín, & Gálvez Ruiz, 2019), using FracLac plugin from ImageJ® software. Dbc was obtained as the average value from at least three processed images. The fractal dimension (D) was obtained as D=Dbc+1 (Palla et al., 2019).

Rheological analysis. Rheological measurements were conducted using a Paar Physica rheometer (Anton Paar GmbH, Austria) with a Peltier temperature control system. A parallel-plate geometry (50 mm) was used to analyze disk-shaped samples taken from the cylindrical containers. Oscillatory strain sweep tests from 0.01 to 100% at 10 rad/s were performed to determine the LVR. Frequency sweep tests were conducted from 1 to 100 rad/s at 20 °C (0.1% strain, 1.5 mm gap) to determine the storage (G') and loss (G'') moduli, and complex viscosity (η^*). Three replicates were performed.

Model Fitting. Experimental curves of viscoelastic properties (G' and η^*) obtained from frequency tests were fitted using a power law model (Palla, Giacomozzi, Genovese, & Carrín, 2017):

$$log\, G' = log\, G'_0 + m_{G'} \cdot log\, \omega \quad (1)$$
$$log\, \eta^* = log\, \eta^*_0 - m_{\eta^*} \cdot log\, \omega \quad (2)$$

Where, ω is the angular frequency and $log\, G'_0$, $m_{G'}$, $log\, \eta^*_0$, and m_{η^*} are constants to be determined experimentally.

Apparent yield stress (Y_s). The critical yield strain (γ_c) was obtained from strain tests as the onset value of the G' curves. This value was multiplied with the complex modulus value below γ_c to obtain Y_s (Cotabarren, Cruces, & Palla, 2019).

Fractal dimension based on the weak-link regime for colloidal dispersion. The macroscopic elastic constant of a network of particles is a function of both the spatial distribution of aggregating particles, characterized by the fractal dimension, and the mechanical properties of the particles which make up the network (Narine & Marangoni, 1999). This relationship can be described as:

$$G' = \gamma\, \Phi^m \quad (3)$$
$$m = 1/(3 - D) \quad (4)$$

Where m and γ are constants to be determined experimentally, Φ was assumed for oleogel systems equal to the gelator concentration, and D is the fractal dimension. G' value at 10 rad/s was used as a representative value. From the linearization of Eq. (3), the obtained slope m was used to find D.

Emulsion stability. 7 mL of each emulsion were dispensed into glass tubes to monitor their stability over time. The stability of oleogel emulsions was observed during 60 days at room temperature by a TurbiScan MA 2000 Analyzer (Formulaction, France), using only the backscattering (BS) detector for data collection due to the samples' opacity. A superimposition of sample fingerprints or "stability profile" was obtained, which characterized the stability or instability of the sample at different times. The parameters were represented by a curve showing the percentage of BS light (%BS) as a function of the height sample in mm (stability profiles). After obtaining the stability profiles of the emulsions, they were divided into three zones as follows: bottom, middle, and top of the tube, for analysis purposes.

Statistical Analysis. Values are mean ± standard deviation of the number of replicate measurements in one representative experiment of three independent experiments. Significant differences were analyzed using one-way ANOVA and Tuckey's test (α=0.05) for multiple comparisons. All analyses were done by IBM SPSS Statistics 25 software.

3 Results and Discussion

3.1 Microstructural analysis

Fractal geometry is a mathematical tool for describing complex shapes that cannot be expressed by the four topological dimensions in traditional Euclidean geometry (0-D for points, 1-D for straight lines, 2-D for planes, and 3-D for volumetric objects) (Schowengerdt, 2007). The D is an indicator of the spatial distribution of mass in a colloidal system, the higher the fractal dimension, the more uniformly filled space (smaller or fewer pores) (Blake, Co, & Marangoni, 2014).

In Fig. 1, the micrographs of two samples (RW2 and CW2) and their respective image analysis carried out by FracLac to obtain Dbc are shown as an example. As it can be seen, both oleogel emulsions exhibited needle-shaped crystals, but the crystals in CW2 were longer and more clustered than those of RW2. The same behavior was also found when the remaining samples (RW3 vs. CW3 and RW5 vs. CW5) were compared (data not shown). Table 1 reports the results of the 3D fractal dimension of all oleogel emulsions. RW emulsions showed D values higher than those obtained for CW emulsions, without significant differences among concentrations. On the contrary, CW emulsions showed an increase in D values with the increment of wax content. These results were in agreement with those previously reported for emulsion wax crystals sizes (Merchán Sandoval et al., 2020), corroborating the direct relationship between crystal size and mass distribution.

Table 1. Fractal dimension (D) and rheological parameters of the oleogel emulsions.

	D	$log\ G_0'$ (Pa)	$m_{G'}$ (Pa)	$log\ \eta_0^*$ (Pa.s)	m_{η^*} (Pa.s^2)	Y_s (Pa)
RW2	2.83±0.01^{D}	2.84±0.06^{A}	0.103±0.005^{AB}	2.85±0.06^{A}	0.89±0.00^{AB}	4.08±0.31^{A}
RW3.5	2.82±0.01^{D}	3.94±0.03^{C}	0.105±0.006^{AB}	3.96±0.03^{C}	0.89±0.01^{AB}	66.31±3.51^{B}
RW5	2.83±0.01^{D}	4.46±0.02^{D}	0.113±0.003^{B}	4.53±0.12^{D}	0.88±0.00^{A}	287.85±74.87^{C}
CW2	2.69±0.01^{A}	3.74±0.09^{B}	0.097±0.001^{A}	3.75±0.09^{B}	0.90±0.00^{B}	48.04±14.07^{B}
CW3.5	2.72±0.01^{B}	4.34±0.07^{D}	0.105±0.007^{AB}	4.36±0.07^{D}	0.90±0.00^{AB}	217.90±8.79^{C}
CW5	2.78±0.01^{C}	4.94±0.03^{E}	0.115±0.008^{B}	4.96±0.04^{E}	0.88±0.01^{A}	1498.87±274.42^{D}

Data are expressed as mean values ± standard deviation of three replicates. In each column, values with different letters are significantly different ($p < 0.05$).

3.2 Rheological analysis

From frequency sweep tests, elastic modulus (G') and complex viscosity (η^*) curves of all oleogel emulsions were obtained (Fig. 2a, b, c and d). For all samples, it was observed that G' showed a small dependence on frequency (ω), which indicated a strong gel-like behavior (Tavernier, Doan, Van der Meeren, Heyman, & Dewettinck, 2018). CW emulsions were found to have higher G' values than RW emulsions at the same amount of wax. Furthermore, G' showed a dependence of wax concentration for both

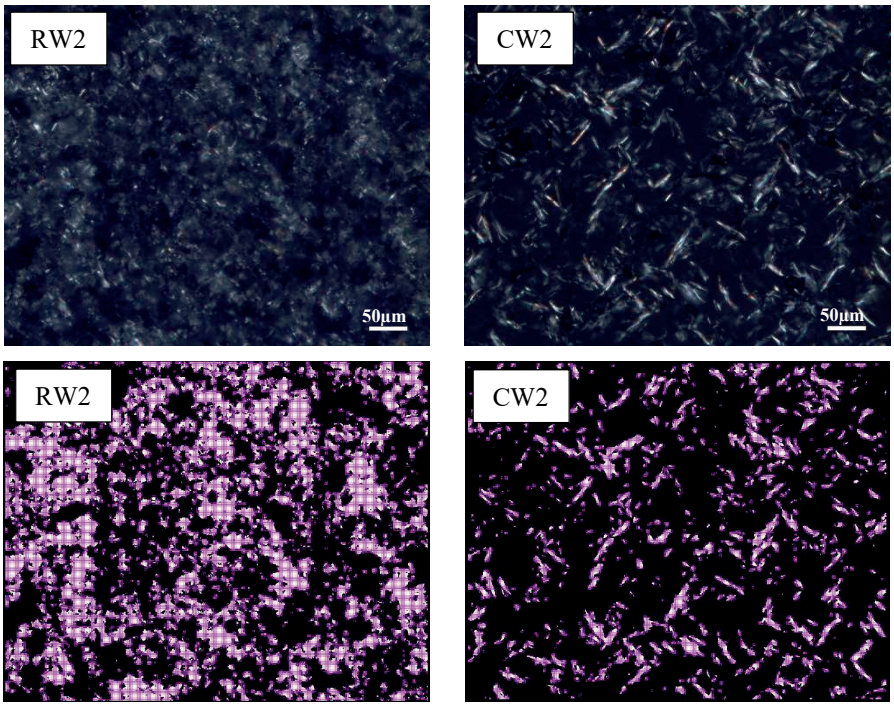

Fig. 1. Micrographs of oleogel emulsions formulated with 2% of recovered sunflower waxes (RW2) and commercial sunflower waxes (CW2). Original images (top) and processed image by FracLac using box-counting analysis (bottom)

oleogel emulsions, since higher wax contents displayed higher G' values. This behavior indicated that more elastic emulsions were obtained due to the presence of a greater amount of wax crystals.

Regarding to η^* behavior, it was observed that η^* values decreased as the frequency increased, showing a process of disaggregation of the wax clusters into smaller pieces (Patel, 2015). Similar to G', the η^* values of the CW emulsions were higher than those of the RW emulsions comparing the same wax content, and it was also observed that the η^* value increased as the amount of wax increased in both oleogel emulsions.

The G' and η^*curves of all oleogel emulsions were properly fitted by Eq. (1) and Eq. (2), respectively, since all the fits presented a high R^2 value (> 0.993). The values of the parameters for both models are given in Table 1. The parameter $log\ G'_0$, which is associated with G' magnitude, increased with the wax content for both CW and RW oleogel emulsions. Furthermore, CW emulsions presented higher $log\ G'_0$ values than RW emulsions for the same wax concentration. The parameter $m_{G'}$ was slightly higher as the wax content increased for both the RW and CW emulsions, but there was no difference between RW and CW for the same amount of wax. Related to $log\ \eta^*_0$, their values showed a similar behavior than those observed for $log\ G'_0$. However, the parameter m_{η^*} did not present a clear trend, which indicated that the frequency-dependence of η^* of all samples was similar.

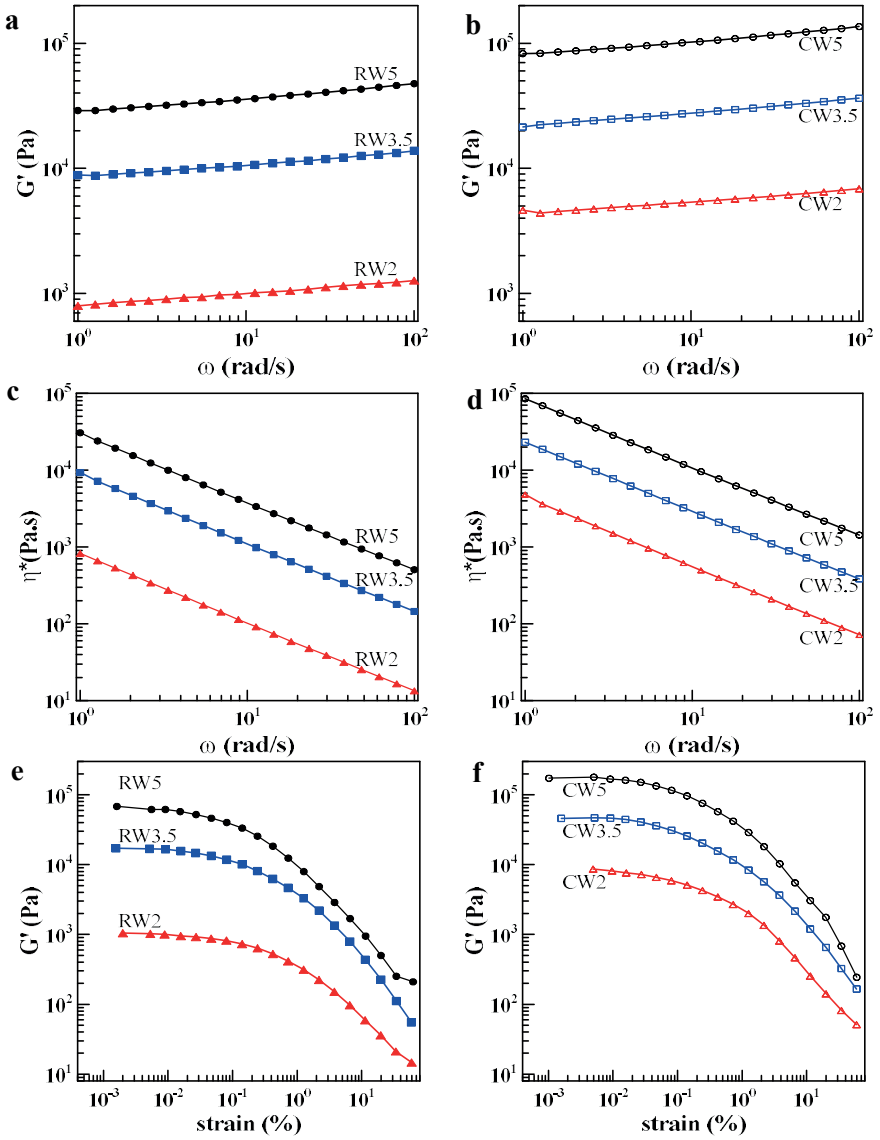

Fig. 2. Rheological behavior of oleogel emulsions formulated with recovered sunflower waxes (RW) (a, c and e) and commercial sunflower waxes (CW) (b, d and f) at 2%, 3.5%, and 5% w/w wax in oleogel. Elastic moduli (G') (a and b) and complex viscosity (η^*) (c and d) from frequency sweep tests and G' (e and f) from oscillatory strain sweep tests.

Oscillatory strain tests are used to evaluate the linear viscoelastic region of materials, and can also be employed to determine the apparent yield stress (Y_s) which can be related to spreadability and material stability (Cotabarren, Cruces, & Palla, 2019; Sun & Gunasekaran, 2009). The G' curves versus strain (%) of oleogel emulsions are displayed

in Fig. 2e and f. Similar to G' and η^* frequency curves, the G' strain curves of CW emulsions presented higher values than RW emulsions and also greater values as the wax content increases.

The Y_s is the point at which deformation of solid becomes liquid-like when stress increases (Truong, Prakash, & Bhandari, 2019) and is associated with the quality and consumer acceptance of spreadable foods (Daubert, Tkachuk, & Truong, 1998). As can be seen in Table 1, Y_s increased as the wax amount increased for both CW and RW oleogel emulsions. For the same wax content, the CW emulsions showed higher Y_s values. The Y_s value of CW5 was comparable to that reported for margarine at 19°C (1200 Pa ± 100 Pa) by Daubert et al. (Daubert et al., 1998) and are placed in the range of easy spreadability products.

The fractal dimension from the weak-link regime approach was determined from the regression slope (Fig. 3) as a unique value for each type of emulsion, being 2.76±0.01 and 2.68±0.02 for RW and CW emulsions, respectively. These results agreed with the trend found on D values from image analysis. The fact that RW emulsions with higher D values presented lower values of G', η^* and Y_s suggests that additional factors affected these properties, such as the presence of "impurities" (Merchán Sandoval et al., 2020) that could have weakened the structural network or the existence of a more disordered molecular arrangement with weaker crystal-crystal interactions.

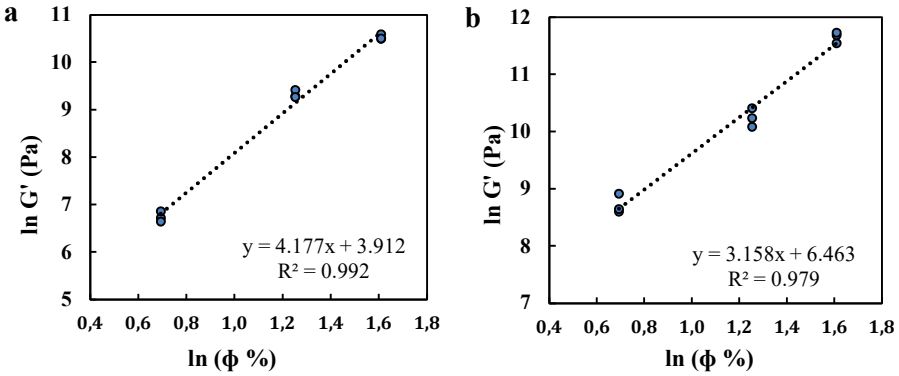

Fig. 3. ln G'as a function of gelator concentration (ln (ϕ %)) for oleogel emulsions formulated with recovered sunflower waxes (RW) (a) and commercial sunflower waxes (CW) (b). The dotted lines in both graphs represent the best fit line through the points, calculated by linear regression. The slope (m) was used to calculate D from Eq. 4.

3.3 Emulsion stability

The stability profiles were divided into three zones: bottom, middle, and top of the tube, for analysis purposes. Migration phenomena are related to the variation of BS in the bottom and the top zones, while particle size variations are related to BS changes in the middle region (McClements, 1999).

The destabilization kinetics of the top of the tubes are shown in Fig. 4a and Fig. 4b for RW and CW, respectively. The increment in the wax content for RW emulsions

caused more stable emulsions, with the destabilization rate being higher for RW2, compared to RW3.5 and RW5. For CW emulsions, it is possible to note that CW5 and CW2 showed curves with similar slopes, while CW3.5 emulsion was more stable showing a more constant profile on time.

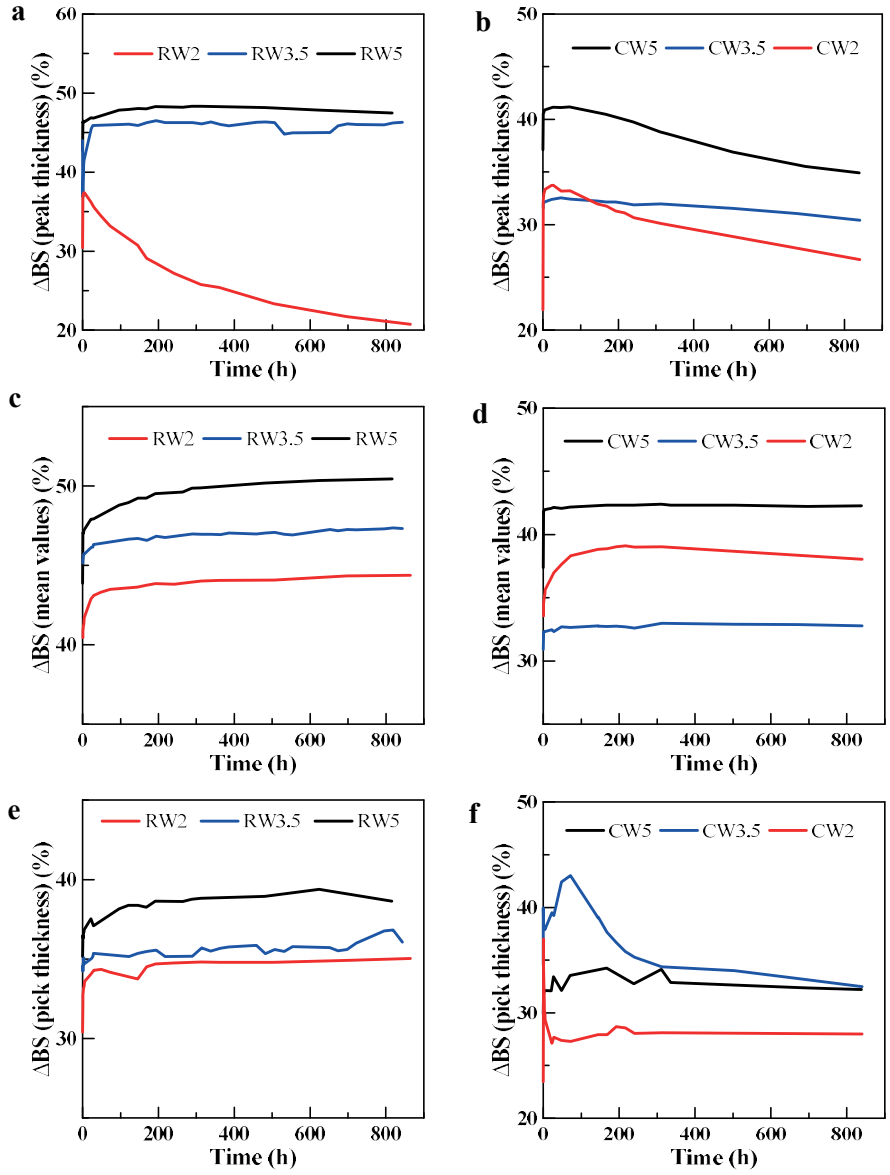

Fig. 4. Destabilization kinetics of oleogel emulsions formulated with recovered sunflower waxes (RW) (a, c and e) and commercial sunflower waxes (CW) (b, d and f) at 2%, 3.5%, and 5% w/w wax in oleogel. Top (a and b), middle (c and d), and bottom zone (e and f) of the tube.

The coalescence destabilization kinetics measured in the middle region for RW oleogel emulsions is shown in 4c. The slope of the curves is similar, indicating that the destabilization speed was not affected by the wax content. The same behavior was observed for CW emulsions (4d).

The destabilization kinetics of the bottom of the tubes are shown in Fig. 4e and Fig. 4f for RW and CW, respectively. For RW emulsions, the destabilization speed seems to be the same, despite the increase in wax content in the emulsion. CW emulsions exhibited similar behaviors, except for the CW3.5 emulsion with a destabilization rate decreasing after 250 hours (10 days) of measurements.

In general, the kinetic stability of both types of oleogel emulsions was not affected by the presence of a greater amount of microstructural elements and therefore, a relationship between D and kinetic stability was not found in the present study.

4 Conclusions

The fractal dimension of CW oleogel emulsions correlated well with the rheological behavior of emulsions. However, RW emulsions showed that besides D, other microstructural characteristics such as molecular arrangement and interactions should be evaluated to achieve a better understanding between micro- and macroscopic behavior. The kinetic stability of both types of oleogel emulsions was not affected by the presence of a greater amount of microstructural elements and therefore, a relationship between D and kinetic stability was not found in the present study.

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Simulación matemática de un Desolventizador-Tostador industrial

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Resumen El trabajo presenta un modelo matemático para simulación de un equipo Desolventizador-Tostador (DT), usado en la eliminación de solvente del producto sólido harina en la industria de producción de aceite y harina a partir de semillas de oleaginosas. El modelo considera el equipo dividido en tres zonas, en las que se plantean los balances microscópicos de masa y energía con parámetros geométricos, que son integrados en las bandejas que conforman cada una de las zonas. Estas son: Zona de Precalentado (ZPC), Zona de Desolventizado con Frente de Receso y Calentamiento (ZDFRC), y Zona de Desolventizado y Tostado (ZDT). Balances macroscópicos con datos de literatura son resueltos preliminarmente para inicializar las variables del sistema algebraico-diferencial riguroso de la simulación. El modelo fue implementado y resuelto en la plataforma R. Se presentan resultados de perfiles de concentraciones de solvente en las fases sólida y vapor, así como temperaturas en las diferentes zonas del equipo. El modelo predice coherentemente estos perfiles constituyendo una herramienta computacional útil para diseño y simulación operativa de un equipo DT industrial.

Palabras clave: desolventizador-tostador, modelado matemático, desolventización

1. Introducción

En la producción industrial de aceite y harina a partir de semillas de oleaginosas, luego del proceso de extracción del aceite mediante solvente, habitualmente hexano, la torta residual queda con un importante contenido de solvente. La eliminación del mismo se lleva a cabo en un equipo conocido como desolventizador-tostador (DT: Desolventizer-Toaster por su nombre en inglés). Esta etapa es una de las más críticas del proceso, no solo porque determina la calidad final de este

producto para su comercialización, sino porque representa uno de los principales ítems del costo operativo debido al alto consumo de vapor que implica. En esta etapa también se produce el tostado de la harina, que le confiere las características finales para su uso como alimento balanceado para animales.

El DT posee una serie de bandejas en las cuales la harina sólida saturada con hexano es calefaccionada indirectamente con vapor, y además puesta en contacto directo con el mismo a través de una corriente ascendente. El vapor permite calentar y vaporizar el solvente en el interior de las partículas sólidas y arrastrarlo para su eliminación del equipo. Operativamente la harina ingresa por tope y el vapor por fondo como vapor vivo y lateralmente a las bandejas huecas como vapor indirecto. La mezcla de vapor-hexano sale por tope y el sólido libre de solvente y con un proceso adicional de tostado por fondo. El sólido circula en forma descendente por el movimiento giratorio de las bandejas y el accionar de paletas que mueven la torta sólida y la pasan a la bandeja inmediata inferior [1].

Debido al elevado consumo energético de los equipos DTs, resulta de interés optimizar su operación para acotar los costos operativos de la planta. Esto ha originado el interés de la comunidad científica por abordar el problema. Sin embrago, si bien existen varios trabajos donde se describe el proceso de desolventización y los diferentes equipos existentes [1, 2], son relativamente pocos los que abordan el desarrollo de modelos matemáticos de simulación de equipos DTs de escala industrial.

Cardarelli y col. [3, 4], presentan un modelo del proceso controlado por difusión que ocurre en la sección de desorción del solvente absorbido en el sólido. En Pramparo y col. [5] se presenta un modelo de tipo semi-empírico, con parámetros estimados en base a datos de planta, en particular la relación entre el contenido de hexano en el vapor y la concentración de hexano en el sólido. Sobre la base del modelo matemático de un absorbedor presentado por Burningham y Otto [6], Paraíso y col. [7] desarrollaron un modelo de un desolventizador consistente en una columna con etapas donde se resuelven balances de masa y energía macroscópicos. Posteriormente Cauneto y col. [8] introdujeron varias actualizaciones a este modelo, permitiendo la incorporación de vapor directo en cualquiera de las etapas, considerando la condensación de agua en el sólido que desciende, empleando regresiones más precisas para el cálculo de propiedades termodinámicas, y obteniendo así un modelo más riguroso.

Sin embargo, estos modelos tienen algunas limitaciones. En el caso del de Cardarelli y col. [3, 4], no tiene en cuenta los balances de energía y solo se aplica a una parte de un equipo, aunque incorpora algunos parámetros geométricos de las unidades industriales, así como de las partículas de sólido y las isotermas de sorción. Por su parte los otros modelos de Paraíso y col. [7] y de Cauneto y col. [8] no tienen en cuenta las características geométricas del equipo industrial, ni las propiedades del sólido y los fenómenos de transporte. Por último, el modelo de Pramparo y col. [5] requiere de información de planta para ser utilizado.

Recientemente, Coletto y col. [9] presentaron un trabajo donde se adopta un enfoque más detallado de modelado, postulando la división del equipo industrial en cuatro zonas (precalentamiento, pre-desolventizado con frente de receso,

pre-solventizado con calentameinto y desolventizado-tostado), cada una con sus características particulares y con un modelo específico. El trabajo se basa en el de Cardarelli y col. [4] para la zona de desolventizado-tostado y presenta un nuevo modelo para la zona de precalentamiento, permitiendo tener predicciones coherentes del perfil de contenido de hexano en el sólido a medida que éste pasa por las zonas modeladas del equipo.

En este trabajo se presenta un modelo mejorado del de Coletto y col. [9], incorporando mayor detalle en diferentes secciones, con el objetivo de obtener una herramienta matemática que permita simular y optimizar el equipo para asistir en el diseño y operación del mismo.

2. Métodos

Al igual que el modelo propuesto anteriormente [9], el DT ha sido subdividido en zonas acorde a los fenómenos que ocurren a lo largo del equipo. Sin embargo, como se muestra en la Fig. 1, el mismo ha sido dividido en tres zonas en vez de cuatro: Zona de Precalentado (ZPC), Zona de Desolventizado con Frente de Receso y Calentamiento (ZDFRC), y Zona de Desolventizado y Tostado (ZDT). En este nuevo modelo dos zonas del modelo anterior han sido unificadas en la ZDFRC debido a que ha sido posible aplicar el mismo modelo a ambas.

El sólido ingresa por la ZPC la cual abarca las tres primeras bandejas o "pisos" del equipo para el caso aquí considerado. La ZDFRC está contenida en un pequeño segmento de la cuarta bandeja, es decir, es el ingreso a la primer bandeja en contra-corriente descrita por Kemper[1], donde tienen lugar diversos fenómenos en simultáneo, como condensación del agua contenida en el vapor ascendente, evaporación del hexano contenido en el sólido, y consecuente disminución en la temperatura de rocío del vapor.

En el sólido la evaporación de hexano ha sido descrita mediante el modelo de Frente de Receso, el cual postula que a medida que disminuye el contenido de solvente por debajo de la saturación líquida de poros, comienza a crecer una capa "seca de solvente", generándose una resistencia conductiva a la transferencia de calor [10, 11]. Así, el sólido está separado en dos partes: una seca y una húmeda, y el solvente está en equilibrio en la interfase. La evaporación ocurre en el frente móvil que avanza hacia el interior de la partícula utilizando toda la energía proveniente del medio externo para la evaporación. Consecuentemente, los perfiles de temperatura y humedad pueden ser despreciados en la región húmeda, y la temperatura del sólido húmedo en hexano puede ser considerada prácticamente constante e igual a la de ebullición. Al llegar a la concentración de hexano de equilibrio (sin líquido en los poros de las partículas), el sólido empieza a aumentar su temperatura hasta llegar a igualar aproximadamente a la del vapor ascendente donde es considerado el fin de la ZDFRC. Durante este proceso, el contenido de hexano va disminuyendo por desplazamiento de su isoterma de sorción.

Finalmente, la parte restante de la cuarta bandeja, y las bandejas sucesivas son consideradas dentro de la ZDT. En dicha zona, a medida que disminuye el

contenido de hexano en el vapor dentro de los poros del sólido, se desplaza el equilibrio de sorción y absorción en el sólido y el aceite, respectivamente. Para este caso ha sido aplicado un sub-modelo doble-escala similar al de Cardarelli, realizando además el balance de energía para ambas escalas.

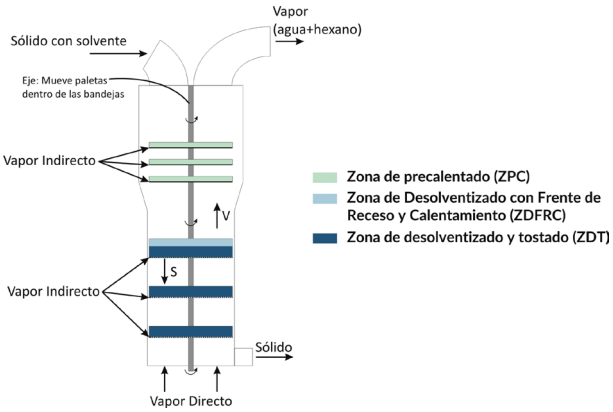


Figura 1. División en zonas para el modelado matemático.

2.1. Zona de Precalentado (ZPC)

En la ZPC la única fuente de energía es el calor indirecto proveniente desde el fondo de cada bandeja, mientras que el vapor ascendente proveniente desde la cuarta bandeja circula por el espacio lateral circundando a las mismas. En esta zona, el sólido llega a la temperatura de ebullición del hexano, pudiendo empezar a evaporarse e integrándose a la corriente de vapor ascendente. En el modelo de la ZPC cada bandeja es discretizada en n_z celdas, suponiendo una distribución uniforme del sólido y sus propiedades, y que cada celda recibirá la misma cantidad de calor volumétrico (calor indirecto dividido volumen de sólido en la bandeja). Dado que no hay vapor ascendente en los espacios interpartícula proveniente del resto del equipo, el único vapor que eventualmente puede haber es de hexano evaporándose. Así, a los efectos de los balances de materia y energía, la harina es contemplada como una mezcla uniforme, y son tomados valores medios de mezcla para el cálculo de sus propiedades termofísicas.

De este modo, los balances microscópicos de materia y energía son integrados al volumen de las celdas,teniendo en cuenta no solo el calentamiento sino también la posibilidad de inicio de la evaporación en los respectivos términos surgentes. De modo similar, también son resueltos los balances de materia y energía en el vapor circundante. La Figura 2 describe el procedimiento aplicado en la resolución del modelo de esta zona.

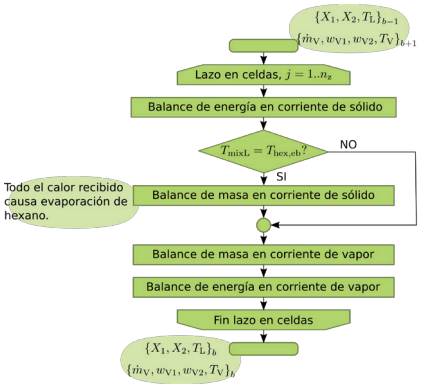


Figura 2. Algoritmo de resolución del modelo de ZPC.

2.2. Zona de Desolventizado con Frente de Receso y Calentamiento (ZDFRC)

Acorde a información de literatura sobre el intercambio de calor y materia en la primer bandeja de contracorriente y curvas de equilibrio de fases del sistema agua-hexano [1] [13], el paso del vapor ascendente es aquí subdividido en dos estadíos; uno de vapor sobrecalentado (V-SCAL) y otro de vapor saturado (V-SAT), siguiendo así el comportamiento de equilibrio vapor/líquido/líquido (EVLL) característico de esta mezcla.

El contenido de hexano de equilibrio a la temperatura de salida en el sólido es estimado suponiendo que la temperatura del sólido a la salida de esta zona es aproximadamente igual a la del vapor ascendente que ingresa a la misma (condición de borde inferior). Además, la cantidad de hexano total que es removido en esta zona es fácilmente calculado conociendo la temperatura y contenido de hexano del sólido al ingreso de la ZDFRC (condición de borde superior), la cual será el hexano total que recibirá la corriente de vapor ascendente en la ZDFRC. La zona es discretizada en celdas en la coordenada axial, y los balances de materia y energía microscópicos son integrados en el volumen de las celdas, suponiendo que en cada celda es removida la misma cantidad de hexano, y despreciando eventual transferencia de agua desde el sólido hacia el vapor. El término surgente para el balance de materia queda conformado únicamente por el intercambio de hexano entre corrientes. En el V-SCAL es tenido únicamente en cuenta el intercambio de calor convectivo en el balance de energía, y a partir del punto en que la composición y temperatura del vapor son los de rocío, es sumada la condensación de agua a todos los balances. La Figura 3 resume el algoritmo de cálculo empleado para la resolución del modelo de esta zona.

2.3. Zona de Desolventizado y Tostado (ZDT)

La harina es considerada como un lecho móvil descendente de partículas que se encuentra con vapor ascendente, y donde ambas corrientes cambian su

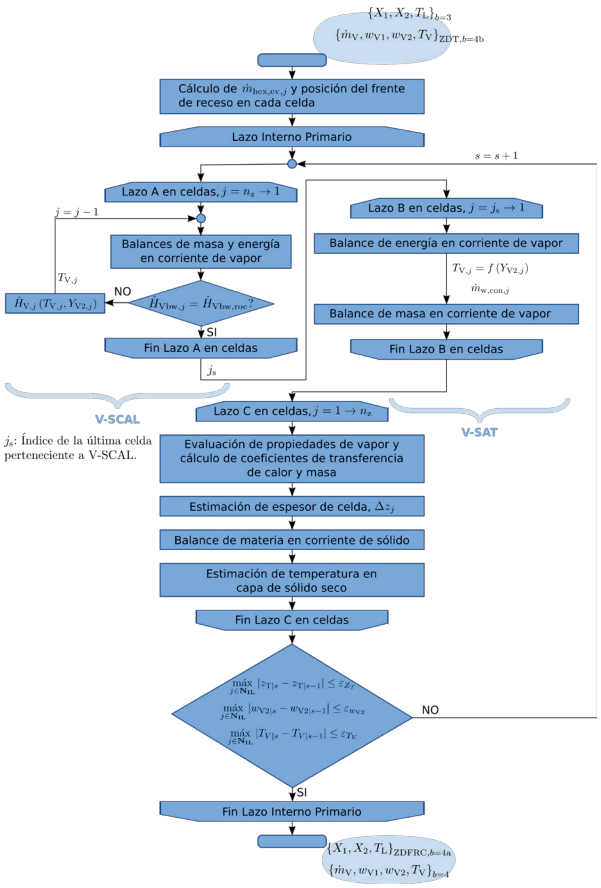


Figura 3. Algoritmo de resolución del modelo de ZFFRC.

composición y temperatura a medida que se desplazan dentro del equipo. En la "escala partícula" los balances de materia y energía determinan el transporte de calor y materia dentro de las partículas individuales, mientras que a "escala lecho" los balances de materia y energía son resueltos para obtener la interacción entre el sólido y el vapor.

La escala partícula tiene en cuenta las fases sólido (s), aceite (o), y gas (g), y supone despreciables los gradientes de temperatura y hexano en las direcciones polar y aximutal. Consecuentemente, el hexano de la fase gas se encuentra distribuido únicamente en la dirección radial dentro de los microporos de manera desuniforme, mientras que la temperatura es idéntica para todas las fases, presentando solamente un perfil de distribución radial. El solvente de la fase gas, a su vez, se encuentra en equilibrio localmente en cada punto de la partícula con el hexano adsorbido en la fase sólida y absorbido en la fase aceite. En cuanto al intercambio de materia y energía, el calor es transferido desde la corriente de

vapor ascendente por convección a la superficie de la partícula, y conducido al centro, mientras el camino opuesto es seguido por el hexano, el cual es transportado difusivamente hacia la superficie y convectivamente transportado por la corriente de vapor ascendente (Figura 4(a)).

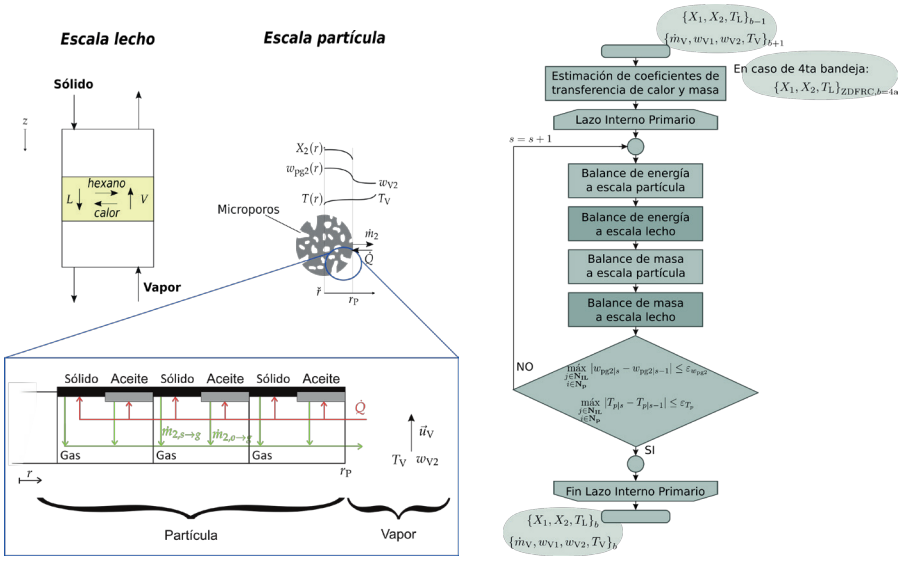
Por otro lado, a escala lecho son despreciados los gradientes radiales y angulares de hexano y temperatura, considerando únicamente la dirección axial. Además, dado que las propiedades del sólido varían únicamente en la dirección axial, se supone que una única partícula representa a todas las presentes a una dada altura del lecho. Así, las propiedades del sólido descendente, tales como temperatura y contenido de hexano, son evaluadas calculando una media volumétrica de los valores obtenidos de la resolución de los balances de materia y energía a escala partícula.

Otras suposiciones realizadas en el modelo de la ZDT son: el proceso es realizado a presión atmosférica con caída de presión despreciable en el equipo; la cantidad de hexano agregado a la corriente ascendente es muy baja, con lo cual es despreciada la variación de densidad del vapor; el contenido de solvente de una única partícula depende del tiempo de residencia o, en otras palabras, de su posición en el lecho. Por lo tanto, el modelo puede ser resuelto como transitorio a escala partícula y de estado estacionario a escala lecho, relacionando ambas escalas con la velocidad del sólido [3, 4]; tanto las fracciones volumétricas de vapor y sólido a escala lecho como las fracciones volumétricas ocupadas por las tres fases a escala partícula son constantes en todo el equipo. En la Figura 4(b) es representado el algoritmo general empleado en la resolución de los distintos balances en la ZDT.

2.4. Algoritmo general de cálculo

En términos generales, dado que el modelo para cada zona requiere condiciones de contorno, las cuales son a su vez las de la zona o bandeja precedente, el simulador es inicializado mediante un balance macroscópico con estimaciones de literatura alrededor de cada zona. Luego los valores de temperaturas y composiciones del sólido y el vapor son interpolados en función de la altura en el equipo para cada bandeja y cada zona (como el caso de la ZDFRC) y los balances en cada bandeja son resueltos de manera modular desde arriba hacia abajo. En el caso de la cuarta bandeja, es resuelto el modelo de la ZDFRC primero, y luego el correspondiente a la ZDT. Esta secuencia se va repitiendo de manera iterativa hasta llegar a convergencia en los valores de temperaturas y composición tanto de la corriente de vapor ascendente como en la de sólido descendente como se muestra en la Figura 5.

En la Tabla 1 son mostrados los valores típicos de entradas al equipo, tanto en composición como caudales, utilizados en el presente trabajo. En cuanto al las características físicas, fue supuesto un equipo de seis bandejas (tres de precalentamiento y 3 de contra-corriente) de 4 m de diámetro cada una. El espesor ocupado por el sólido las bandejas fue de 30 cm para las primeras tres, de 1 m para la cuarta bandeja (contando desde arriba), y de 60 cm para las dos últimas.



(a) Modelo doble-escala, fases y transferencia de calor y materia a escala partícula.

(b) Algoritmo de resolución del modelo de ZDT.

Figura 4. Diagramas del modelo de la ZDT.

En cuanto a las propiedades físicas del sólido e isotermas de sorción fueron utilizados los valores reportados por Cardarelli [3, 4] y Faner [11].

Tabla 1. Valores típicos, utilizados en la simulación.

	Sólido (tope)	Vapor directo (fondo)	Vapor Indirecto
Caudal másico [kg/h]	70.000	8.500	2.500
Temperatura [°C]	58	142	180
		Fracciones en masa	
Agua	0,0900	1,0000	1,0000
Hexano	0,2900	0,0000	0,0000
Aceite	0,0085	-	-
Sólido seco	0,6115	-	-

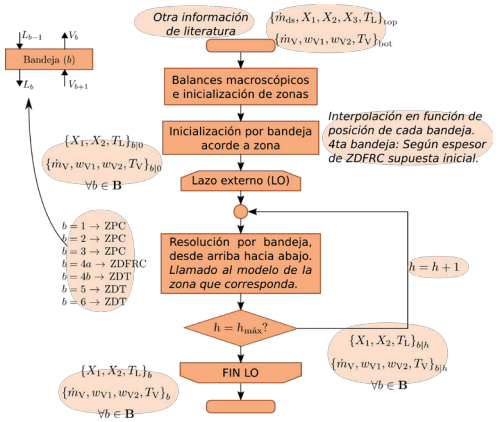


Figura 5. Algoritmo general de cálculo para modelado del desolventizador.

3. Resultados y Discusión

3.1. Simulación global

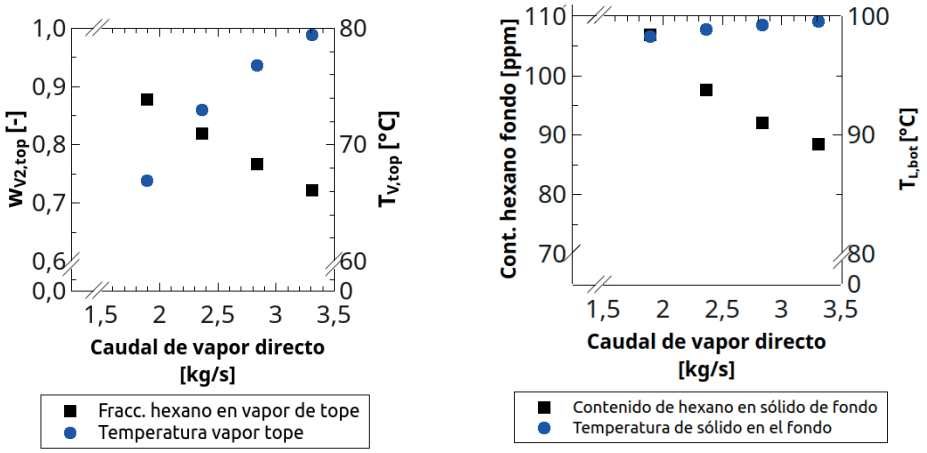
En las Figuras 6(a) y 6(b) son mostrados las temperaturas y contenido de hexano para la salida de la corriente de vapor y de sólido, para variaciones del caudal másico de vapor directo en un rango de ±40 % de un valor típico (2,36 kg/s). Los puntos para 1,42 kg/s (-40 %) no son mostrados dado que en este caso la temperatura del vapor queda por debajo de la temperatura de condensación del hexano y el simulador fue programado para cortar el cálculo en ese caso.

Como podría esperarse, puede notarse que a medida que aumenta la cantidad de vapor directo que ingresa al equipo, las temperaturas de salida tanto del sólido como del vapor aumentan, mientras que el contenido de hexano en ambas disminuye. Sin embargo, se esperaría que la temperatura del sólido a la salida fuera entre 5 y 10°C más. Esta diferencia puede explicarse principalmente teniendo en cuenta las simplificaciones realizadas en el actual modelo de la ZDFRC, donde los efectos de transferencia de calor y materia sobre el sólido son tenidos en cuenta de manera parcial, tomando principalmente lo que ocurre en la corriente de vapor, situación que será resuelta en un nuevo modelo.

Por otro lado, los valores de temperatura de salida del vapor son coincidentes con valores típicos reportados en literatura para el DT descrito [1] [5].

3.2. Zona de Precalentado (ZPC)

En la Figura 7 son mostrados los perfiles de temperatura y contenido de hexano en las tres bandejas de precalentado consideradas. Puede notarse que la evaporación de hexano comienza a fines de la segunda bandeja y avanza en la tercera. Además puede notarse que el comportamiento predicho por el modelo es coherente con lo esperable. Esto es, mientras el sólido se calienta, su concentración de hexano permanece constante, para luego empezar a disminuir cuando su



(a) Salida de la corriente de vapor (tope). (b) Salida de la corriente de sólido (fondo).

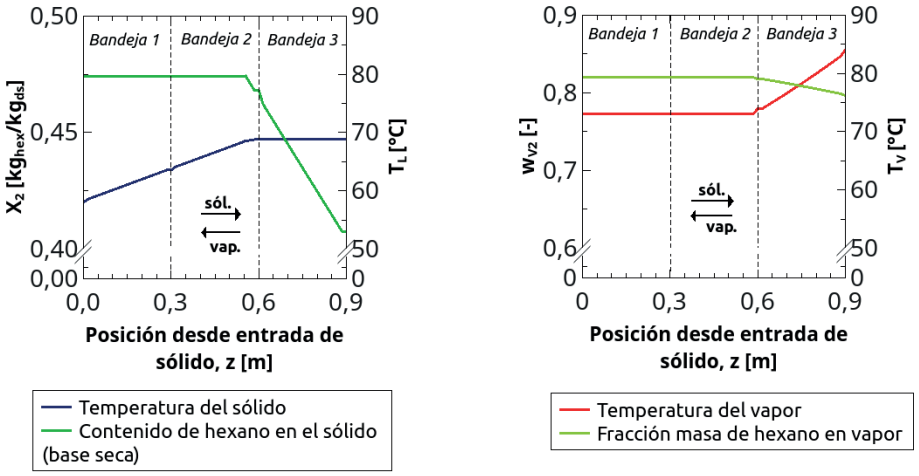
Figura 6. Efectos de la variación del caudal de vapor directo

temperatura alcanza los 68°C (Figura 7(a)). En cuanto al vapor (Figura 7(b)), puede notarse que la fracción en masa de hexano en el vapor en la Bandeja 3 aumenta mientras su temperatura disminuye como producto de la incorporación de hexano vapor a 68°C. Luego, en las Bandejas 1 y 2 mientras continua ascendiendo, estos valores permanecen constantes mientras se produce el aumento de temperatura del sólido. Por otro lado, al final de la ZPC (o última bandeja de predesolventización) el contenido de hexano se ha reducido en un 15 %, en línea con los valores esperables de literatura (10-25 %) [1].

3.3. Zona de Desolventizado con Frente de Receso y Calentamiento (ZDFRC)

El espesor total de la ZDFRC predicho por el modelo ha resultado de aproximadamente 1,6 cm. Debido la falta de información experimental al respecto, y a que este valor además sería sumamente difícil de medir en un equipo industrial, no puede conocerse si el valor real será mayor o menor al calculado. Sin embargo, teniendo en cuenta que debido a la condensación de vapor de agua sobre la superficie expuesta de las partículas, la evaporación del hexano se producirá de manera violenta y abrupta [4, 12], sería esperable que el espesor de la ZDFRC sea sumamente pequeño con respecto a la altura total del material que ocupa la primer bandeja de contra-corriente.

Por otro lado, en la Figura 8(a) puede notarse que en esta zona se produce una reducción de aproximadamente un 94 % del hexano con respecto al ingreso a la misma (lo cual representa una reducción de un 95 % con respecto a la entrada al equipo). Además, teniendo en cuenta que el contenido de aceite en el sólido utilizado en la simulación es de 0,0139 $kg_{aceite}/kg_{s.seco}$, el contenido de humedad



(a) Corriente de sólido.

(b) Corriente de vapor.

Figura 7. Perfiles de contenido de hexano y temperatura en las bandejas de la ZPC.

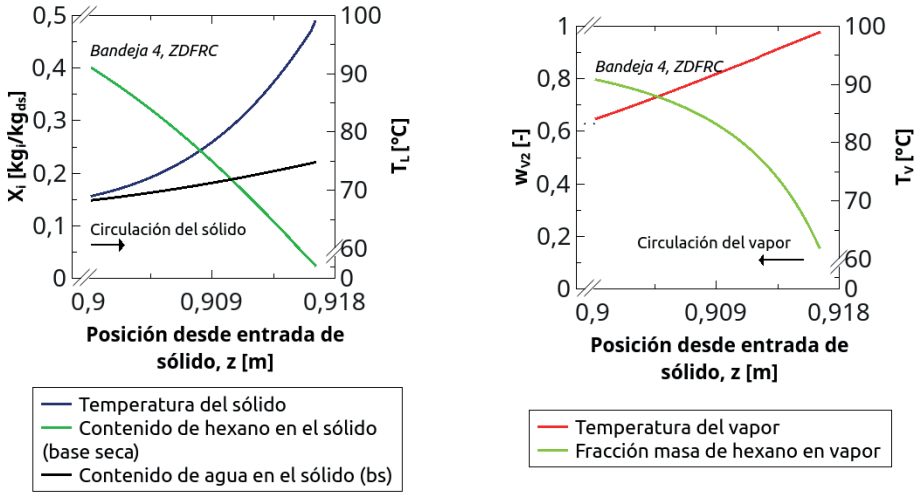
se incrementa de 9 % a 17,5 % en peso. Todo ello se encuentra en concordancia con los valores esperables según literatura especializada.

En cuanto a la temperatura de salida del sólido y de ingreso del vapor a la ZDFRC (Figuras 8(a) y 8(b)), los valores típicos rondan entre 100 y 110°C. Sin embargo, los valores aquí predichos se encuentran por debajo de los 100°C, lo cual es atribuido a los valores estimados por le modelo de la ZDT. En dicho modelo, se supone que parte del calor indirecto pasa al vapor (al atravesar los orificios de la bandeja), y parte pasa al sólido transmitido por conducción en un lecho mixto sólido-vapor, y luego es contemplado dentro del término surgente en el balance de energía a escala partícula. Sin embargo, la parte de calor que va al sólido es estimando mediante el cálculo de un calor conductivo axial por diferencia de temperatura, y calculando la fracción que va al vapor como la diferencia entre el calor indirecto total y dicho valor. Debido a que la diferencia de temperatura entre capas de sólido es prácticamente despreciable, el calor conductivo axial estimado mediante este método puede resultar subestimado.

Como consecuencia de lo anterior, también puede notarse en la Figura 8(b) que no hay estadío V-SCAL para el vapor, ingresando directamente en V-SAT.

3.4. Zona de Desolventizado y Tostado (ZDT)

Como puede notarse en la Figura 9(a), la desolventización en las bandejas pertenecientes a la ZDT avanza mucho más lento debido al control difusivo dentro de las particulas de sólido, a medida que el vapor se va cargando de hexano. El sólido ingresa a la ZDT de la cuarta bandeja con alrededor de 20.000 ppm de hexano, y sale de la ZDT de la última bandeja con alrededor de 100



(a) Corriente de sólido.

(b) Corriente de vapor.

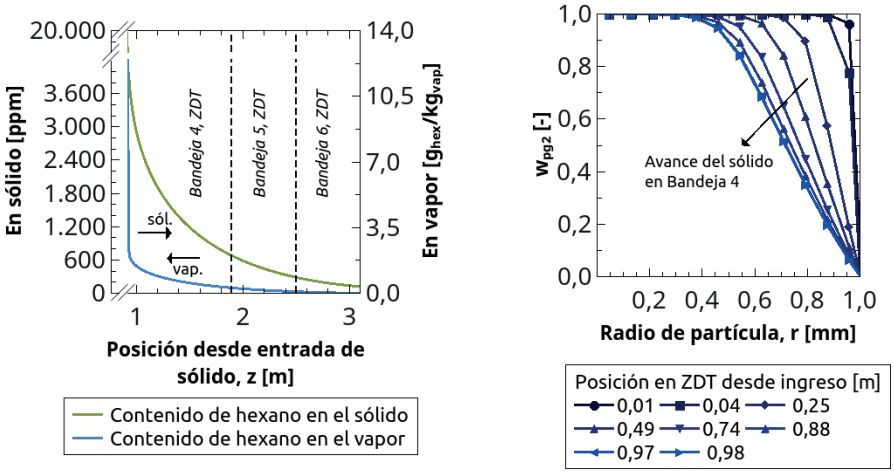
Figura 8. Perfiles de contenido de hexano y temperatura en las bandejas de la ZDFRC.

ppm, valor que se encuentra dentro de los rangos reportados en la literatura. En cuanto al perfil de temperaturas (no mostrado), se mantiene aproximadamente constante a lo largo de las bandejas en donde se encuentra la ZDT. Por las razones antes expuestas, el modelo actual no puede predecir mayores variaciones en la temperatura del sólido.

Por otra parte, en la Figura 9(b) es mostrado el perfil de fracción en masa de hexano dentro de la fase gas de cada partícula, para distintas posiciones del sólido en la cuarta bandeja. Puede notarse que, a medida que el sólido desciende, el contenido de hexano en la fase gas va disminuyendo, resultando en los típicos perfiles de transferencia de materia controlada por difusión (simimilares a los obtenidos por Mattea [12]). Además, estos valores se encuentran en relación directa con el contenido total de hexano en la partícula mediante su relación de equilibrio de adsorción en el sólido y absorción en el aceite.

4. Conclusiones

Se propone una versión rigurosa de un modelo matematico de un DT industrial que posee mayor nivel de detalle que otras publicadas previamente. La división en zonas, donde cada una tiene su propio modelo (que actúa de submodelo del cálculo global), permite describir matemáticamente a cada zona con las ecuaciones que gobiernan los fenómenos que allí ocurren teniendo en cuenta fenómenos de equilibrio termodinámico en la corriente de vapor, adsorción y absorción de hexano en las fases sólida y aceite, y descripción completa del fenómeno difusivo en la última etapa del proceso. Además, si bien no se cuenta



(a) Perfiles de contenido de hexano en la ZDT en corriente de sólido y vapor.

(b) Perfil de fracción en masa de hexano dentro de la fase gas de la partícula para distintas posiciones de la parte ZDT de la cuarta bandeja.

Figura 9. Perfiles de contenido de hexano en la ZDT (bandejas y partícula).

con una completa y detallada información de planta del desolventizador, el modelo integrado arroja resultados dentro de los valores esperables reportados en la literatura.

Por otro lado, se está trabajando en la actualidad en el mejorado del modelo de la ZDFRC con el objetivo de describir mejor el intercambio de energía y, de este modo, mejorar la predicción de la estimación de la temperatura del sólido.

Con todo ello, un modelo riguroso completo permitirá en un futuro, además de simular el funcionamiento del equipo, obtener las condiciones óptimas de entrada al mismo que permitan minimizar el consumo de energía.

Nomenclatura

$\mathbf{B}$	Conjunto de índices de bandejas, b	-
$\hat{H}$	Entalpía específica	J/kg
$\hat{H}_{\mathrm{Vbw}}$	Entalpía específica de la corriente de vapor en base agua	$\mathrm{J/kg_w}$
$\mathbf{N}_{\mathrm{IL}}$	Conjunto de índices de celdas, j	-
r	Coordenada radial en partícula	m
r_{P}	Radio de partícla	m
S_{LQmix}	Término surgente de calor en corriente de sólido de ZPC	$\mathrm{W/(m^3\ )}$
S_{VQ}	Término surgente de calor en corriente de sólido	$\mathrm{W/(m^3\ )}$
T	Temperatura	K
$T_{\mathrm{hex,eb}}$	Temperatura de ebullición de hexano	K
$\mathbf{u}$	Velocidad	m/s
w_i	Fracción en masa de componente i	-
X_i	Contenido de componente i en base seca	$\mathrm{kg}_i/\mathrm{kg_{ds}}$
Y_{V2}	Contenido de hexano en la corriente de vapor	$\mathrm{kg_{hex}/kg_w}$
z	Coordenada axial en el equipo	m
Letras griegas		
Δz	Espesor de celda	m
Subíndices		
1 o w	Agua	
2 o hex	Hexano	
bot	Fondo del desolventizador	
con	Condensada	
ev	Evaporado	
inf	Al final de la zona considerada (borde inferior)	
L	Sólido descendente	
mixL	Corriente de sólido considerada como conjunto harina+espacio inter-partículas	
pg	Fase gas de la partícula	
s,h	Índices de iteración s y h en resolución de modelos particulares de zona y global, respectivamente	
sup	Al inicio de la zona considerada (borde superior)	
top	Tope del desolventizador	
V	Vapor ascendente	

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Comparison between Clarke &Wright and Nearest Neighbor methods on thermal performance of Cold Chain products during generation of distribution route

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Abstract. A major challenge in the physical distribution of Cold Chain products is ensuring product quality while minimizing process costs. In this context, this study seeks to propose a routing model with restrictions by the Clarke and Wright method that considers the behavior of the temperature variation of refrigerated loads during their physical distribution and to compare it with the results obtained through the Nearest Neighbor method. The objective of the study is to propose a simulation tool that is capable of planning routes for the physical distribution of refrigerated products, making the entire logistics process more efficient, reducing the unwanted gain of internal temperature of the vehicle and the product, considering the time windows available, number of vehicles and available capacity. Five scenarios in total were compared and, as a result, the Clarke and Wright method with temperature restriction proved to be more effective for routing within the imposed temperature limits and aiming at savings in the number of vehicles and distance traveled.

Keywords: Cold Chain; Routing; Transport; Cooling.

1 Introduction

The increase in the world population and the usual rush of large cities lead to the consumption of more chilled and frozen foods. Among its advantages are ease and agility in preparation, preservation of sensory, physical and organoleptic properties, increased validity and high quality of products (CARVALHO, 2013). This type of supply chain, known as the cold chain, is defined by Heap (2006) as a chain in which a controlled temperature environment is required to guarantee the integrity of the product handled, from production to the final consumer.

Carvalho (2013) explains that temperature determines the rate of microbial activity in cold chain products, the main cause of the deterioration of this type of food, which can lead to loss of product quality. Another important factor concerns its physical distribution. The distance traveled directly impacts the temperature to which the product

is subjected, as well as its unloading conditions. It is also important to note that the vehicle's cooling is not designed to cool the load, but to preserve it within the proper limits.

Thus, the objective of this article is to propose a model aimed at routing vehicles with restrictions, considering the thermal performance of the transported cargo, distance traveled, window of available time and necessary fleet.

2 Literature review

Dias (2012) defines logistics as the part of the supply chain that plans, programs and controls efficiency, the flow of storage of goods, services and information between the point of origin and consumption. It also defines the supply chain as the union of suppliers with manufacturers, distributors, wholesalers and customers. Therefore, logistics is essential for connecting the supply chain.

The activities of transportation, inventory maintenance and order processing, according to Ballou (2006), represent the largest portions in terms of logistics costs and are essential for the coordination and fulfillment of the logistics task, being a constant concern. Wanke (2011) complements by defining distribution as the development of a system that covers all activities, from the production line to delivery.

2.1 Physical distribution of Cold Supply Chain products

Annually about 300 million tons of products in the cold chain are lost due to a deficient refrigeration process along the supply chain, most of which occurs in the transport process, due to temperature fluctuation (CARVALHO, 2013). Heap (2006) points out that the lack of control of microbiological reactions can lead to cumulative and irreversible losses in product quality.

Pereira et al. (2010) presents as parameters inherent to the process that cause thermal variation: opening of doors, gain of thermal gradient of the external environment, non-uniformity of temperature inside the vehicle and number of stops, in addition to the distance between production and consumption. In the case of long distances, even when transport provides satisfactory temperatures, the travel time can be long for short expiration dates. On the other hand, for shorter deliveries, the refrigerated or frozen product may be subject to many door openings, with heat exchange with the outside air, in addition to the heat acquired by the movement of the operators responsible for removing and delivering the products (PEREIRA et al., 2010).

Another critical point highlighted by Pereira et al. (2010) is that the goods must be shipped with the temperature within the prescribed range, since the vehicle's refrigeration unit is not designed to cool it, but rather to preserve it within the appropriate standards. Therefore, the vehicle must be pre-cooled before loading.

2.2 Routing with restrictions

According to Gama (2011), the physical distribution system has as an element the routing of delivery vehicles, with the objective of obtaining routes that minimize

distribution costs of a fleet of vehicles from one or more central depots, supplying the entire demand. Novaes (2016) indicates that one of the biggest problems in the physical distribution of products is related to the time limits or capacity of the vehicle.

The traveling salesman problem is one of the most classic problems and consists of finding a route of minimum length, starting from a given starting place, visiting a set of points in the best possible order, and returning to the place of origin, using it for that, only the existing paths that connect these points (SANTOS, 2006). Because they are difficult to solve problems, it is common to use heuristic methods (such as the Clarke and Wright method and the Nearest Neighbor method), achieving good results in less time.

Clarke and Wright method. According to Santos and Leal (2007), one of the most used heuristics to solve the VRP problem is the Clarke and Wright algorithm. This method has the flexibility to solve a large number of restrictions relatively quickly in computational terms, generating solutions close to optimality (BALLOU, 2006).

As detailed by Novaes (2016), the method is based on the concept of gain and starts with the worst situation, where each vehicle leaves the distribution center (DC) and serves only one customer before returning. Considering that a customer *j* is served after a customer *i*, the vehicle would travel a distance L of:

$$L = 2 \times d_{D,i} + 2 \times d_{D,j} \qquad (1)$$

From the initial situation, it is sought to find improvements by uniting the two clients *i* and *j* in the same route, making the distance traveled by the vehicle:

$$L' = d_{D,i} + d_{D,j} + d_{i,j} \qquad (2)$$

Joining the two customers *i* and *j* in a single route, savings will be generated equal to the difference between L and L ', equal to:

$$g_{i,j} = d_{D,i} + d_{D,j} - d_{i,j} \qquad (3)$$

The Clarke and Wright method consists of analyzing all possible combinations between the nodes, two by two, ordering the gains $g_{i,j}$ in decreasing order and joining the nodes until the economy is the maximum possible.

Nearest Neighbor method. This method consists of, starting from a point, looking for the point closest to it. Goldbarg and Luna (2000) explain the heuristic how, starting from the vertex of origin, the vertex not yet visited is added to each step, whose distance from the last visited vertex is minimal. The procedure ends when all vertices have been visited. At the end, a connection is made between the last visited vertex and the original vertex.

As Santos (2006) explains, this method is usually used to find an initial solution to the problem, which solution is then gradually improved by other techniques and models. It has simple and fast application and can be used for highly complex problems.

3 Materials and Methods

3.1 Input data

In order to compare the two mentioned methods, the data used were the same used by Müller et al. (2019), presented in Table 1. In the example applied, a complete graph of 8 nodes is considered, where node 1 is the Distribution Center (DC) and the others are product distribution points.

Table 1. O/D Matrix (minutes).

O/D	1	2	3	4	5	6	7	8
1	0	14,14	8,39	20	14,14	21,27	15	25,03
2	14,14	0	16,82	31,62	28,28	32,83	20	15,28
3	8,39	16,82	0	14,86	16,05	27,59	22,53	30,73
4	20	31,62	14,86	0	14,14	29,19	31,62	44,79
5	14,14	28,28	16,05	14,14	0	15,06	20	37,67
6	21,27	32,83	27,59	29,19	15,06	0	15,06	36,03
7	15	20	22,53	31,62	20	15,06	0	20,97
8	25,03	15,28	30,73	44,79	37,67	36,03	20,97	0

To use the data in the program, the O/D matrix was converted from minutes to kilometers, considering the average speed of the truck during distribution 40 km/h.

The demands considered for each node were 310, 165, 155, 500, 300, 210 and 360 kg, respectively, the capacity of each vehicle is 2.000 kg, the maximum working day is 24 hours, the point of temperature abuse is -10°C and the stopping time at each node depends on the amount of product to be discharged, as shown in Equation 4, according to Müller et al. (2019).

$$downtime = 297{,}61 * demand - 0{,}1348 \qquad (4)$$

These data were imputed in the scenarios considered in the next section, in order to discover a good routing method for the case study.

3.2 Temperature calculations

The calculations of temperature variations that occurred during the physical distribution process of Cold Chain products that were applied in this study were based on the studies by Müller et al. (2019). Therefore Equation 5 was adapted from these authors.

$$\theta(\tau) = \theta_{source} + (\theta_0 - \theta_{source}).\exp\left(-\beta.\frac{\tau}{m}\right) \qquad (5)$$

Where $\theta(\tau)$ (K) represents the product temperature in time τ (minutes), θ_0 (K) is the initial product temperature, m (%) is the product mass ratio contained in the truck, β is the coefficient of temperature variation, shown in Equation 6, and θ_{source} (K) is the temperature that the system exerts on the product, assuming the value of 4°C when the vehicle is moving between one point and another, and 20°C when the product is being

downloaded from a given customer. For the calculation of β values, the equation was used:

$$\beta = \frac{\ln\left(\frac{\theta_j}{\theta_{j-1}}\right)}{\frac{dt_{j-1,j}}{m}} \qquad (6)$$

Since θ_j (K) is the air temperature at point *j*, θ_{j-1} (K) is the initial product temperature at point *j*-1, m (%) the total mass ratio contained in the vehicle, dt (minutes) the time interval between points *j*-1 and *j*.

Therefore, for each visited point the value of β was calibrated and $\theta(\tau)$ was calculated twice, once for the period of displacement and once for unloading. For the starting point, DC, the θ_j considered was -40°C, also according to the proposal by Müller et al. (2019).

The implementations of the methods of Clarke and Wright and the Closest Neighbor were made in C ++ in order to determine the minimum fleet necessary for physical distribution, supplying all the demand, without exceeding the capacity of each vehicle and the established time windows, covering the shortest possible distance and respecting the temperature limits.

4 Results and discussions

Initially, it is proposed to analyze the initial scenario, generated by the model without considering temperature control, only considering the routing heuristic. The graphs resulting from each route, considering the thermal performance over time, are also presented, as well as all the information of the generated routes.

The main results generated by the simulation include the number of vehicles needed for the fleet, the route to be taken by each vehicle with their respective distances, the average and maximum temperatures reached during the distribution and the time spent on each journey.

4.1 Initial scenario

The initial scenario considered was that of the highest possible cost, where each vehicle supplies only one node, leaving and returning to the DC. The total cost considered is given by the distance to be covered by all routes, that is, it is the sum of the distances covered by each route. Thus, the initial total cost is 157,29 km, with seven routes to be covered and seven vehicles required for distribution. The routes are represented in Figure 1 and described in Tables 2 and 3.

As expected, temperatures did not even come close to reaching the point of abuse, since the distributor serves only one customer per trip, and there is no time for excessive temperature rise. The increase in temperature as a function of time for each route is shown in Figure 2.

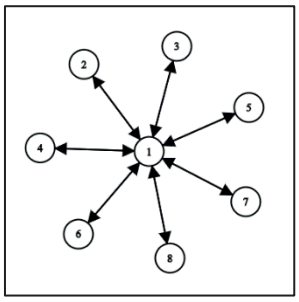

Fig. 1. Representation of the routes generated by the initial scenario.

Table 2. Routes generated by the initial scenario

Route	Path	Demand (kg)	Journey (h)	Distance (km)	Average temperature (°C)	Maximum temperature (°C)
1	1 - 2 - 1	310	1,24	18,85	-28,22	-23,43
2	1 - 3 - 1	165	0,69	11,19	-28,22	-23,43
3	1 - 4 - 1	155	1,05	26,67	-28,22	-23,43
4	1 - 5 - 1	500	1,71	18,85	-28,22	-23,43
5	1 - 6 - 1	300	1,45	28,36	-28,22	-23,43
6	1 - 7 - 1	210	1,02	20,00	-28,22	-23,43
7	1 - 8 - 1	360	1,72	33,37	-28,22	-23,43

Table 3. Results generated for the initial scenario.

Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
7	-23,43	-28,22	No	157,29

It is important to note that, although the method is quite attractive in terms of temperature values, it has a high cost for the distributor, which would need to have a vehicle for each customer, not being an economically viable option.

Although it is not feasible, the initial scenario will be used for comparison with the other scenarios, since, from there, it seeks to improve the number of vehicles used in the distribution of products, in order to keep temperatures below the point of abuse and reduce the total distance to be covered. It is important to note that each generated route corresponds to a different vehicle, as a vehicle cannot travel two routes simultaneously. Therefore, in this study it was considered that the number of vehicles needed for the fleet will be the number of routes generated by the program.

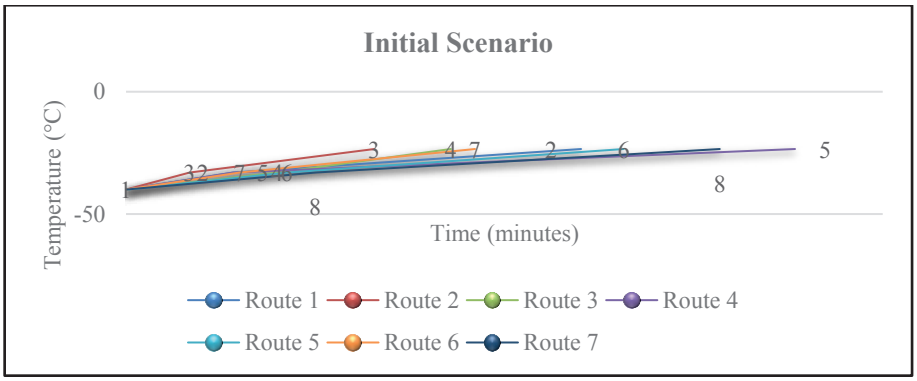

Fig. 2. Temperature variation of routes generated by the initial scenario.

4.2 Scenario 1: routing with C&W without temperature restriction

In this scenario, the results of the first application of Clarke and Wright will be presented, without the use of any temperature restriction of the products along the route. The routes found, as well as their specificities, are described in Tables 4 and 5 and in Figure 3.

Table 4. Routes generated by the scenario 1.

Route	Path	Demand (kg)	Journey (h)	Distance (km)	Average temperature (°C)	Maximum temperature (°C)
1	1 - 2 - 8 - 1	670	2,56	36,30	-22,93	-17,06
2	1 - 3 - 4 - 5 - 6 - 7 - 1	1330	4,66	55,01	-14,07	-3,60

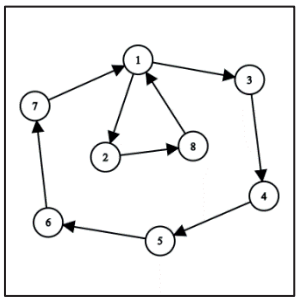

Fig. 3. Representation of the routes generated by the scenario 1.

Table 5. Results generated for the scenario 1.

Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
2	-3,91	-18,54	Yes	91,31

The minimum total distance found was 91,31 km, a value that will be used for comparison with the other scenarios, as well as their temperatures. In the generated route, the temperature exceeds -10°C during the unloading of cargo at point 5 of Route 2. Figure 4 illustrates the behavior of the temperature along the route, where this abuse is better evident.

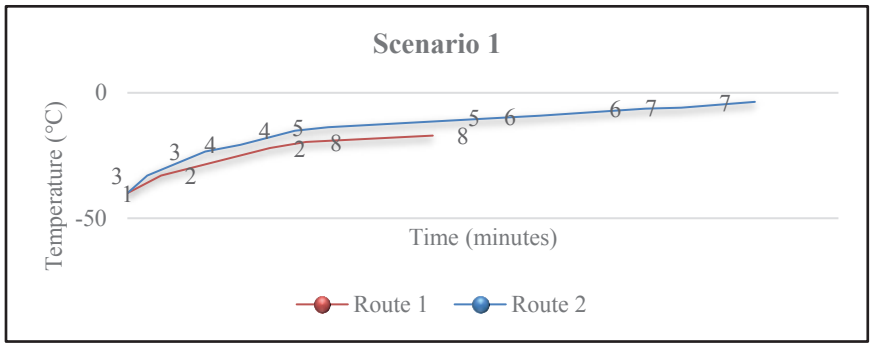

Fig. 4. Temperature variation of routes generated by the scenario 1.

4.3 Scenario 2: routing with C&W with temperature restriction

This scenario has the same heuristic as scenario 1, however blocking routes that reach the point of temperature abuse. Because of this restriction, there was an improvement in temperature values, as expected, increasing the distance covered, as shown in Tables 6 and 7 number of routes, and the number of routes as shown in Figure 5.

Table 6. Routes generated by the scenario 2.

Route	Path	Demand (kg)	Journey (h)	Distance (km)	Average temperature (°C)	Maximum temperature (°C)
1	1 - 2 - 8 - 1	670	2,56	36,30	-22,93	-17,06
2	1 - 3 - 4 - 1	320	1,51	28,83	-23,05	-15,06
3	1 - 6 - 7 - 1	510	2,12	34,22	-23,05	-15,06
4	1 - 5 - 1	500	1,71	18,85	-28,22	-23,43

Table 7. Results generated for the scenario 2.

Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
4	-15,06	-24,31	No	118,21

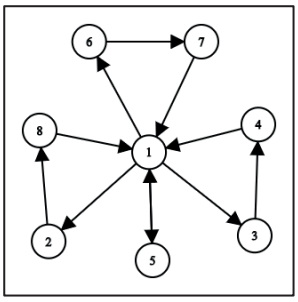

Fig. 5. Representation of the routes generated by the scenario 2.

The temperature variations along the described routes are illustrated in Figure 6.

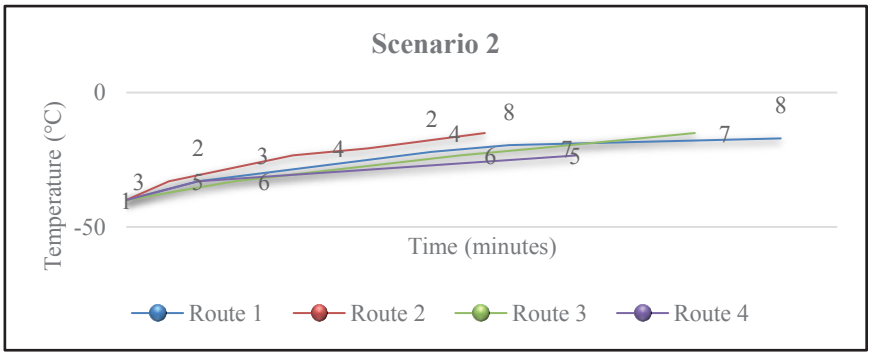

Fig. 6. Temperature variation of routes generated by the scenario 2.

It is observed that this scenario provides lower values of temperature compared to scenario 1, with a difference of 11,15°C in the maximum temperature and 5,77°C in the average temperature, being necessary to consider the advantage of the increase in distance covered (26,9 km) and the required fleet (with two more vehicles) in relation to this decrease.

4.4 Scenario 3: routing with Nearest Neighbor without temperature restriction

The method used in this scenario is simpler than the previous one, based only on the search for a route with the shortest total distance to be covered. As this scenario relaxed the temperature restriction, it was possible to generate only one route, including all the 7 nodes (distribution points), and, considering the total vehicle capacity of 2.000 kg (as declared in Section 3.1), it was possible to attend all the demand. Figure 7 illustrates the generated route, with a total distance of 78,60 km, lower in 14% when compared to the Scenario 1 (Clark and Wright without temperature restriction). Its major disadvantage is in the temperature values, as can be seen in Tables 8 and 9, which exceeded the point of temperature abuse. If compared with Scenario 1, the temperature results

were worst, increasing the maximum obtained temperature in 4,06°C. The increase in temperature during the route is shown in Figure 8, where it can be seen that, from point 5 onwards, the point of abuse is reached and exceeded by up to 10,15°C.

Table 8. Routes generated by the scenario 3.

Route	Path	Demand (kg)	Journey (h)	Distance (km)	Average temperature (°C)	Maximum temperature (°C)
1	1 - 3 - 4 - 5 - 6 - 7 - 8 - 2 - 1	2000	7,24	78,60	-10,50	0,15

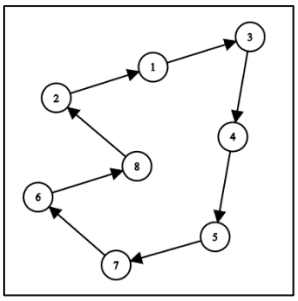

Fig. 7. Representation of the routes generated by the scenario 3.

Table 9. Results generated for the scenario 3.

Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
2	0,15	-10,5	Yes	78,6

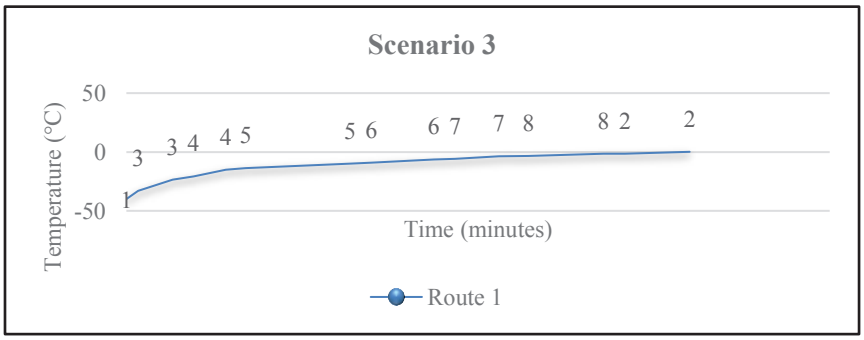

Fig. 8. Temperature variation of routes generated by the scenario 3.

This method, therefore, is not particularly good for a situation like the one in this case study, where temperature variation is a fundamental factor for product quality.

4.5 Scenario 4: routing with Nearest Neighbor with temperature restriction

In order to try a better solution than scenario 3, scenario 4 was generated, which considers the restriction of the abuse point on the route. As a consequence, there were four routes more than scenario 3, as shown in Figure 9, and, in addition, the distance also increased from 78,60 km to 127,23 km, as can be seen in Tables 10 and 11. The maximum and average temperatures were -15,06°C and -26,13°C for scenario 4, while in scenario 3 they were 0,15°C and -10,5°C.

Table 10. Routes generated by the scenario 4.

Route	Path	Demand (kg)	Journey (h)	Distance (km)	Average temperature (°C)	Maximum temperature (°C)
1	1 - 3 - 1	165	0,69	11,19	-28,22	-23,43
2	1 - 4 - 1	155	1,05	26,67	-28,22	-23,43
3	1 - 5 - 1	500	1,71	18,85	-28,22	-23,43
4	1 - 2 - 8 - 1	670	2,56	36,30	-22,93	-17,06
5	1 - 6 - 7 - 1	510	2,12	34,22	-23,05	-15,06

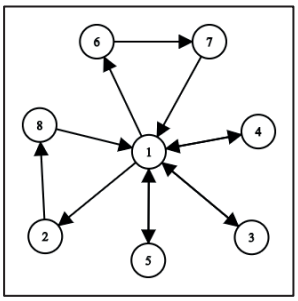

Fig. 9. Representation of the routes generated by the scenario 4.

Table 11. Results generated for the scenario 4.

Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
5	-15,06	-26,13	No	127,23

Representing what has already been described in the tables, Figure 10 shows the temperature variations over time for each route. With the insertion of the temperature restriction, this scenario generated better results, even with the increase of the distance (of 61,87%) in relation to scenario 3, since, in this case, the temperature reached is a fundamental factor for the choice of the route.

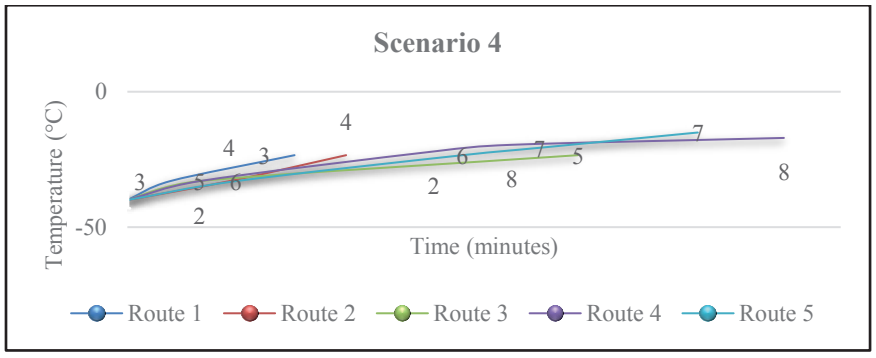

Fig. 10. Temperature variation of routes generated by the scenario 4.

4.6 Scenarios comparison

Since the objective of the study is to suggest a method for routing the distribution of products in the Cold Chain and a very important factor for the product to maintain its quality is the temperature at which it is maintained during the transport operation, the comparison between the scenarios were due to factors such as the maximum and average temperature reached in each scenario, in addition to the fact of having or not having abuse of temperature at some point, as shown in Table 12.

Table 12. Scenario results.

Scenario	Vehicles	Maximum temperature (°C)	Average temperature (°C)	Temperature abuse	Total distance (km)
Initial	7	-23,43	-28,22	No	157,29
1	2	-3,91	-18,54	Yes	91,31
2	4	-15,06	-24,31	No	118,21
3	2	0,15	-10,5	Yes	78,6
4	5	-15,06	-26,13	No	127,23

From Table 12, only scenarios that did not contain temperature abuse were selected. Therefore, the initial scenario, scenario 2 and scenario 4, highlighted in the table, were selected. From these, other comparative analyzes were carried out ignoring the remaining scenarios, as they are outside the study's field of interest.

Analyzing the maximum and average temperatures reached in the three selected scenarios, it is noticed that the initial scenario has the lowest values for temperatures (-23,43°C and -28,22°C, respectively). However, when observing the number of vehicles needed for the fleet and the total distance to be covered, the method does not become advantageous, since the distributor would need to have a vehicle for each delivery point, not being a sustainable possibility for the company. Therefore, the initial scenario was eliminated due to lack of viability.

With this, the ideal for choosing the best method between scenarios 2 and 4 is to consider together the values of the required fleet, maximum and average temperatures and total distance covered. For this specific case, there is no need to compare the maximum temperature as it is identical (-15,06°C) in both scenarios. Therefore, three criteria were considered: total number of vehicles needed, average temperature in °C and total distance traveled in kilometers, as shown in Figure 11.

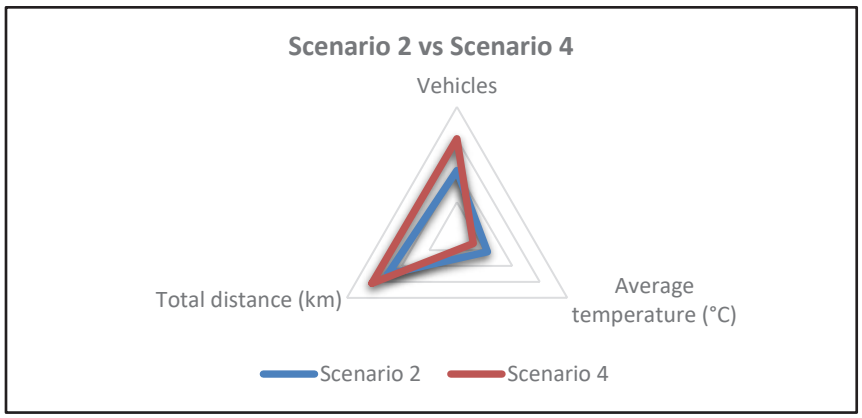

Fig. 11. Radar chart for comparison between scenarios 2 and 4.

It can be seen in Figure 11 where each scenario is better or worse. Scenario 2 requires one vehicle less than Scenario 4, in addition to traveling a shorter distance during the distribution of products, in 9,02 km, being more advantageous in these two criteria. Scenario 4 is more advantageous in the average temperature, with a difference of 1,82°C. Such advantages and disadvantages are summarized in Table 13.

Table 13. Differences between scenarios 2 and 4**.**

Scenario	Vehicles	Average temperature (°C)	Total distance (km)
2	4	-24,31	118,21
4	5	-26,13	127,23
Δ	1	1,82	9,02

Despite the difference of 1,82°C in the average temperature, it is important to realize that both temperatures are far from reaching abuse, not making this an advantageous criterion. The number of vehicles is an important indicator of advantage for scenario 2, greatly reducing costs for the distribution company during the distribution of Cold Chain products. The total distance traveled also represents such an advantage, even though it is not an expressive value. Because of this, the scenario with the best results for the case study was scenario 2, that is, the one generated through the Clarke and Wright method added by the temperature restriction.

5 Conclusions

The increase in the world population and the fast pace of life today mean that customers from different places demand large quantities of fresh or frozen food products. An important factor for the conservation of these foods is the storage temperature, both at the origin and destination, and in the displacement between them. Although there are refrigeration options for vehicles, it is very important to carry out a routing study so that the route taken by the distributor is effective. Factors such as the distance between delivery points, the amount of product to be unloaded at each point, as well as the time required for such activity, in addition to the time windows available for the service, must be taken into account.

In this study, two heuristic methods (Clarke and Wright and, Closest Neighbor) were considered, creating four possible scenarios for scripting, based on the example proposed by Müller et al. (2019), where the maximum and average temperatures reached on each generated route and the minimum total distance traveled were compared, since for the distribution company it is very important that the quality of the product is combined with a viable negotiation cost.

In the initial scenario, the proposal is to have a vehicle for each delivery point, which easily proves to be an unfeasible strategy for a given company, due to the high cost of capital and high idleness of the vehicle and the employee. For the following scenarios, the strategy of proposing the same routing method was used, but adding temperature restrictions imposed or not. For scenarios 1 and 3, this restriction is relaxed, unlike scenarios 2 and 4. When it comes to cases without restriction, these brought very attractive values for the total distance covered, however the temperatures reached exceed the point of abuse, which can decrease the quality of the products, and it is not interesting for the company that supplies the product or even for the customer that receives it. Thus, the scenarios analyzed in order to propose the best routing method were 2 (Clarke and Wright method) and 4 (Nearest Neighbor method).

Considering the two selected scenarios, four variables were considered as important for decision making: the required fleet, the maximum temperature reached, the average temperature during distribution and the total distance covered on each route. As the variables were not initially hierarchical, they were analyzed one by one in order to compare the advantages and disadvantages for each of the two scenarios. As a result, scenario 2 was similar to scenario 4 at the maximum temperature reached (-15,06°C) and was more attractive in terms of the required fleet (4 vehicles) and the total distance covered (118,21 km). Analyzing the only item in which scenario 4 was better, it is clear that there is not much difference between them and that, even scenario 2, has a very attractive value for it, not getting close to reaching temperature abuse. Therefore, scenario 2 was considered the best method for routing the case study in question, that is, the Clarke and Wright method generated better results, which was to be expected since this considers the maximum savings in the elaboration of the routes, achieving good results for the covered distance, managing to restrict the result to the restrictions imposed.

It is important to note that, with the increase in the number of delivery points and demand, the complexity of the problem also increases. In the considered example, the

total load demanded did not exceed the capacity of the truck and the number of delivery points did not require the fulfillment of the entire workday of the distributor. In order to meet greater demands without the need to increase the fleet and less idle vehicle, without interfering with the quality of the cargo, a good practice is to negotiate the time windows available for delivery, allowing the same delivery person to make more than one trip, even if it is necessary to return to the DC for refueling.

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Evaluación tecnológica en bodega de una levadura vínica patagónica previamente propagada en un sustrato no convencional

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En los últimos años, la vitivinicultura nacional recuperó el lugar de relevancia que históricamente tuvo dentro de las agroindustrias. En la región del Comahue (Patagonia noroccidental) este renacer de la vitivinicultura se tradujo en una significativa reactivación de la actividad en las áreas productivas históricas (Alto Valle de Río Negro) y en el desarrollo de nuevas áreas (Departamento de Añelo, provincia del Neuquén). Actualmente la producción regional está mayoritariamente orien- tada a la elaboración de vinos tintos jóvenes y secos (80%) de variedades neutras de vid como Mal- bec y Merlot [1], contando la región con condiciones agroecológicas óptimas para expresar todo su potencial enológico [2]. No obstante, una economía globalizada, manejada por el consumo y mer- cados exigentes por productos cada vez más selectos, impone a los vitivinicultores regionales nuevos desafíos que requieren de innovación tecnológica. Mientras la vinificación es un proceso complejo desde el punto de vista ecológico en el que las levaduras, responsables de conducir la fermentación primaria o alcohólica (FA), desempeñan un rol protagónico, las tendencias innovadoras de la eno- logía actual están mayoritariamente orientadas a la exploración de las propiedades del vino relacio- nadas con este recurso microbianos y a su manejo adecuado mediante el uso de cultivos iniciadores de la FA [3].

Los cultivos iniciadores son cultivos puros de cepas de levaduras especialmente selecciona- das por sus propiedades para uso en enología que se comercializan bajo la forma de levadura seca activa (LSA) y que previa rehidratación se adicionan al mosto fresco en altas densidades celulares con el fin de normalizar la biota asociada al proceso fermentativo y rendir vinos de calidad contro- lada. Existe evidencia que variaciones geográficas observadas en la composición de las poblaciones microbianas asociadas a terruños vitivinícolas se correlacionan con las características organolépticas distintivas de los vinos elaborados en ellos, permitiendo proponer el concepto de "terroir micro- biano" [4, 5 y 6], comunidades constituidas por especies y cepas de

microorganismos típicas de la zona geográfica de producción del vino [7]. En este contexto, la conducción de las vinificaciones mediante el uso de cultivos iniciadores (*starters*) autóctonos de cada terruño es actualmente una tendencia en expansión en la vitivinicultura mundial con el fin de agregar valor a los vinos mediante el control y la diferenciación de su calidad [8].

Con el objetivo de desarrollar cultivos iniciadores de la FA autóctonos de la Patagonia, ac- tualmente inexistentes en el mercado, en trabajos previos se caracterizaron la diversidad específica e intraespecífica de la biota levaduriforme asociada a uvas, mostos de fermentación y superficie de bodegas de la región del Comahue seleccionándose diversas cepas autóctonas con propiedades ade- cuadas para uso enológico [9]. Una de estas cepas, *Saccharomyces cerevisiae* F8 (*Sc* F8 propagada en pie de cuba fue evaluada en vinificaciones regionales a escala piloto con excelentes resultados [10] proponiéndose su producción a nivel industrial en la forma de LSA para su comercialización como cultivo iniciador.

1. Objetivo del trabajo

Evaluar a escala industrial (Bodega) la capacidad de esta cepa autóctona *S. cerevisiae* F8 de conducir exitosamente vinificaciones en tinto regionales otorgando carácter diferencial en la calidad del vino previa propagación de su biomasa en un sustrato no convencional.

2. Metodología y resultados

Las células de *Sc* F8 se propagaron a escala piloto utilizando un sustrato no convencional abundante en la región como es el bagazo de manzanas (medio EBM) [11] en sistema de cultivo por lotes a 30°C [12]. Previa evaluación de su calidad sanitaria y microbiológica por métodos convencionales y moleculares [12], la biomasa húmeda se inoculó en 15.000L de mosto Malbec sulfitado (Bodega Favretto, Villa Regina, Vendimia 2019). Los controles fueron vinificaciones conducidas por cultivos comerciales ampliamente utilizados en vinificaciones en tinto regionales, *S. cerevisiae* F15 de Laf- fort (*Sc* F15, LSA) o por la bodega elaboradora, *S. cerevisiae* Bacofer de Tudela (*Sc* BA, levadura líquida). La cinética de las fermentaciones alcohólicas (FA) se siguió por evolución de los grados Baumé (°Bmé) y de la temperatura, y la capacidad de implantación de las cepas por recuento de viables en GPY agar y análisis molecular para identificación de especies (ITS PCR/RFLP) [13] y discriminación de cepas (ADNmit/RFLP con *Hinf*I) [14] El análisis fisicoquímico de los vinos se realizó conforme a los métodos propuestos por el Instituto Nacional de Vitivinicultura (INV) y el sensorial mediante una prueba de preferencia realizada por 17 enólogos regionales de vasta expe- riencia profesional. En esta prueba los diferentes vinos elaborados se identificaron con diferentes letras (A, B y C) debiendo el consumidor asignarle a cada vino un valor 1, 2 o 3 según su preferencia. Uno, el preferido en primer lugar, dos en segundo lugar y tres en tercer lugar. En esta degustación a ciegas, el promedio obtenido para cada vino es más cercano a uno cuanto mayor es su preferencia

por el consumidor.

Todas las vinificaciones conducidas mostraron cinéticas correspondientes a FA normales (Fi- gura 1) y los ensayos moleculares de discriminación a nivel de individuos evidenciaron que las tres cepas de *S. cerevisiae* son capaces de implantarse, entendiendo por implantación la capacidad de dominar numéricamente a la biota indígena, y conducir la exitosamente la FA (datos no mostrados). No obstante, los cultivos autóctonos presentaron un inicio de fermentación y un secado mosto más rápido que los comerciales (Figura 1) completando el proceso 48 h antes que éstos. Esta mayor actividad fermentativa no se tradujo en una mayor temperatura del proceso, que nunca superó los 22°C (Figura 1), evidenciando una mayor iciencia energética de la cepa autóctona acreditada por la menor disipación de energía en forma de calor respecto de sus contrapartes comerciales. Ambos comportamientos del cultivo autóctono son de gran importancia industrial por sus efectos positivos sobre los costos de producción (reducción de tiempo y energía).

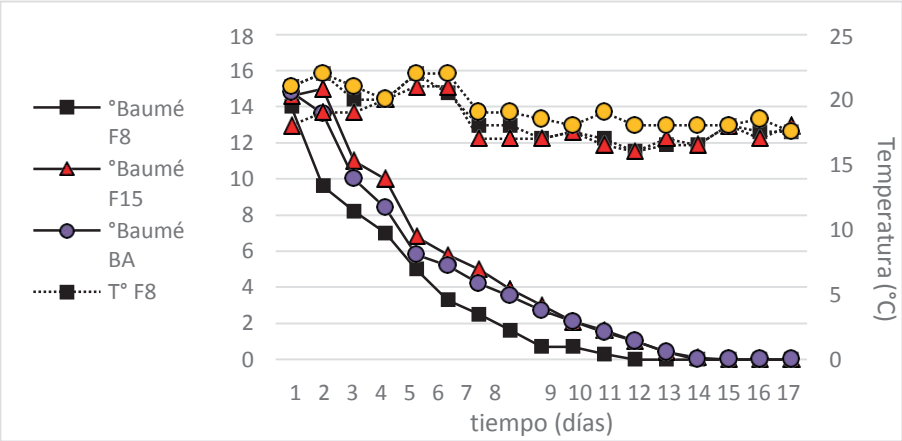

Figura 1: Cinética de las fermentaciones alcohólicas de las vinificaciones en tinto Patagónicas conducidas por los cultivos iniciadores autóctono (*Sc* F8) y comerciales (*Sc* F15 y *Sc* BA).

Los vinos presentaron características fisicoquímicas de vinos normales, aunque *Sc* BA fue incapaz de secar el mosto (ART>2 g L^{-1}) debido a su mayor dificultad de fermentar la fructosa respecto de la glucosa (Tabla 1). El cultivo iniciador autóctono y *Sc* F15 presentaron buena capacidad para fer- mentar ambos monosacáridos y menores concentraciones de ácido málico y mayores de ácido láctico en sus vinos en relación a las observadas en el elaborado con *Sc* BA indicando una mayor permisi- vidad de estos cultivos para el desarrollo de la maloláctica que la *Sc* BA. La FML, descarboxilación enzimática del ácido L-(-) málico en ácido L-(-) láctico realizada por las bacterias del ácido láctico

es una fermentación secundaria opcional deseable en la elaboración de los vinos tintos porque in- crementa su estabilidad microbiológica y su complejidad aromática [15].

Finalmente, el análisis sensorial realizado por los consumidores mediante pruebas de prefe- rencia (Tabla 2) indican que el vino elaborado con el cultivo autóctono *Sc* F8 obtuvo el mejor promedio, pero, por el tamaño muestral analizado, la diferencia no fue significativa respecto de la preferencia por el elaborado con el *Sc* F15, pudiendo concluirse que los consumidores mostraron una mayor preferencia por los vinos elaborados con los cultivos iniciadores *Sc* F8 y *Sc* F15 que por el elaborado con BA.

Tabla 1: Calidad fisicoquímica de vinos Malbec obtenidos en la Vendimia 2019 mediante fermentaciones alcohólicas conducidas por cultivos iniciadores autóctono puro (*Sc* F8) comerciales (*Sc* BA y *Sc* F15)

Parámetro	**VINOS**		
	***Sc* F8**	***Sc* BA**	***Sc***
Etanol % v/v	13,74	13,90	13,67
ART (g L^{-1})	1,90	2,86	2,21
pH	3,81	3,80	3,82
Acidez Titulable (g L^{-1})*	5,09	5,77	5,06
Acidez Volátil (g L^{-1}) □	0,40	0,30	0,29
Fructosa (g L^{-1})	0,74	2,03	0,91
Glucosa (g L^{-1})	0,27	0,73	0,55
Ácido Málico (g L^{-1})	0,41	1,44	0,81
Ácido Láctico(g L^{-1})	0,98	0,50	0,92
Glicerol (g L^{-1})	7,74	7,42	6,95

ART: azúcares reductores totales. *Expresado como g L^{-1} de Ácido Tartárico. □ Expresado como g L^{-1} de Ácido Acético.

Tabla 2: Prueba de preferencia de los consumidores por los vinos elaborados me- diante fermentaciones alcohólicas conducidas por cultivos iniciadores autóctonos (*Sc* F8) y comerciales (*Sc* F15 y *Sc* BA)

VINO	**PREFERENCIA**			
	Promedio	***Ranking***		
		1	**2**	**3**
Sc F8	1,65±0,17[a]	8	5	4
Sc F15	1,94±0,19[a]	7	8	2
Sc BA	2,41±0,21[b]	2	4	1

Medias con superíndices diferentes, son significativamente diferentes, modelo lineal gene- ralizado y prueba de DGC con $p<0,05$ y n=17. [16]

3. Conclusión

La capacidad demostrada por la biomasa de la levadura *Sc* F8 propagada en medio EBM de iniciar rápidamente la fermentación, implantándose satisfactoriamente, conduciendo el pro- ceso hasta el completo secado del mosto y rindiendo vinos con características sensoriales dife renciales y de preferencia por los consumidores permite concluir que el proceso de propagación propuesto conserva en la cepa las propiedades tecnológicas por las que fuera seleccionadas reafirmando a escala industrial la aptitud de esta levadura para uso enológico como cultivo iniciador autóctono de la Patagónica.

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Extracción de compuestos bioactivos de frutillas cv. Albion tratadas con ozono en fase acuosa y almacenadas en refrigeración, y evaluación de sus propiedades antioxidantes

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Resumen. En los últimos años se ha estudiado el potencial del ozono como estrategia postcosecha en diversos productos frutihortícolas. En estudios previos, los autores desarrollaron tratamientos de ozono en fase acuosa capaces de reducir la incidencia fúngica y la pérdida de peso durante el almacenamiento refrigerado de frutillas cv. Albion. El objetivo de este trabajo fue evaluar el efecto de dichos tratamientos en el contenido de compuestos bioactivos y la capacidad antioxidante de frutillas cv Albion durante el almacenamiento a 5 ± 1 ºC, para lo cual se realizó la puesta a punto de una metodología de extracción asistida por ultrasonido. Los frutos fueron sumergidos en la columna de tratamiento previamente cargada con 1,25 L de agua destilada, y sometidos durante 5 y 15 minutos a un burbujeo de ozono (18 mg $O_3.L^{-1}$ en la corriente de alimentación a la columna) a 20 ± 1 ºC, y posteriormente almacenados en bandejas de polipropileno a 5 ± 1 ºC. El contenido de compuestos bioactivos y la capacidad antioxidante de los frutos ozonizados y sin tratar (control) fueron evaluados a los 0, 4 y 8 días de almacenamiento. Las condiciones óptimas de extracción resultaron: $V_{solvente}$ = 80 mL; Amplitud = 60 %; Tiempo = 15 min. La acumulación de antocianinas totales (AT) dependió de la dosis de ozono aplicada, resultando en una disminución significativa para el tratamiento de 15 min. Por el contrario, el contenido de fenoles totales (FT) y la capacidad antioxidante no se vio afectada por ninguna de las dosis evaluadas.

Keywords: Ozono, Frutilla, Antioxidantes

1 Introducción

En los últimos años diversos estudios han evaluado la efectividad de los tratamientos con ozono en fase gaseosa o acuosa en la extensión de la vida postcosecha de diversos frutos y vegetales [1]. El mecanismo de acción del ozono radica en su elevado poder oxidativo, que ocasionaría daños en componentes celulares vitales que conllevan a la inhibición del desarrollo microbiano, como así también a un efecto indirecto asociado a la inducción de mecanismos de defensa de la matriz vegetal. Esta respuesta resulta dosis-dependiente y está asociada a la inducción de sistemas antioxidantes, la acumulación de compuestos fenólicos con actividad antimicrobiana, el refuerzo de paredes celulares, entre otros [2-4]. La identificación y cuantificación de los compuestos fenólicos en frutillas ha sido ampliamente reportado, incluso para diferentes cultivares y en distintos estadios de madurez [5,6]; como así también los potenciales beneficios que la ingesta de los mismos tendría para la salud humana [7,8]. La evidencia existente respecto al efecto de los tratamientos con ozono sobre el contenido de antocianinas, compuestos fenólicos y capacidad antioxidante no es concluyente y revela la necesidad de realizar estudios sistemáticos que permitan arribar en forma más precisa a las condiciones óptimas de tratamiento. En estudios previos se ha demostrado que el tratamiento con ozono en fase acuosa de frutillas cv. Albion permitió reducir la incidencia fúngica y la pérdida de peso durante el almacenamiento refrigerado, sin afectar las propiedades mecánicas de dichos frutos [9].

Con el fin de maximizar los rendimientos en cuanto a la extracción de antocianinas y compuestos fenólicos totales en frutillas, se han evaluado distintas mezclas extractoras, como así también diferentes metodologías de extracción y de separación de dichos compuestos [10-12]. Un aspecto a tener en cuenta a la hora de evaluar el efecto de distintos tratamientos poscosecha en los atributos antioxidantes de las frutas es obtener un extracto concentrado de estos compuestos sobre el cual se puedan realizar la mayor cantidad posible de determinaciones. En base a estudios previos del grupo donde se evaluó la efectividad de distintas mezclas extractoras para la extracción de compuestos bioactivos de frutillas [13], se encontró que la extracción por maceración utilizando una mezcla extractora de etanol-ácido clorhídrico 0,1N (85:15 v/v) permitió obtener un buen rendimiento en la cuantificación de estos compuestos, pero el tiempo de extracción resultó muy prolongado (24 horas). La extracción asistida por ultrasonido se ha propuesto, entre otras técnicas convencionales y no convencionales, para maximizar la obtención de compuestos de interés de frutas y matrices vegetales en general y/o incrementar la velocidad de extracción [10,14].

Los objetivos de este trabajo fueron 1-optimizar una técnica de extracción asistida por ultrasonido para la evaluación de las propiedades antioxidantes de frutillas, y 2-evaluar el efecto de la aplicación de ozono en fase acuosa en el contenido de compuestos bioactivos y la capacidad antioxidante de frutillas cv. Albion durante el almacenamiento a 5 ± 1 ºC.

2 Materiales y métodos

2.1 Materia prima

Se utilizaron frutillas cv. Albion con grado de madurez comercial (100% color rojo), provenientes de un productor local de la zona de Pilar, provincia de Buenos Aires. Los frutos fueron clasificados según su tamaño y se descartaron aquellos que presentaron anormalidades fisiológicas, daño mecánico, deterioro microbiológico o bien, que no tuviesen la madurez indicada.

2.2 Tratamientos con ozono

Se utilizó un generador de ozono por descarga corona modelo UTK-O-4 (Unitek S.A., Argentina), y oxígeno como gas de alimentación a una temperatura de 20 ± 1 ºC. El ozono proveniente del generador se inyectó por la parte inferior de la columna de tratamiento, previamente cargada con 1,25 L de agua destilada y 10 frutillas (~200 g). En base a estudios previos [9] se determinó la concentración de ozono disuelto en función del tiempo de tratamiento, que luego de 5 min de estabilización resultó en una concentración residual de 3,5 ± 0,5 $mg.L^{-1}$.

Los frutos fueron expuestos a 5 y 15 min de tratamiento con ozono. El tratamiento de 5 min fue elegido por su desempeño en la inhibición de la micobiota nativa y en otros parámetros de calidad evaluados [9], mientras que el de 15 min se seleccionó en el objeto de evaluar el efecto de una exposición al ozono más prolongada. Luego de los tratamientos con ozono, los frutos fueron secados con papel absorbente, empacados en bandejas de polipropileno permeables al aire (10 frutillas/bandeja) y almacenadas a 5 ± 1 ºC. Se consideraron frutos control a las frutillas sin tratar y almacenadas en las condiciones antes descriptas.

2.3 Extracción de compuestos bioactivos

Se evaluó la extracción asistida por ultrasonido utilizando un diseño factorial de 3^3 (factores: volumen de solvente, amplitud de onda de ultrasonido y tiempo de sonicación) aumentado en 8 puntos centrales; cada condición se realizó por duplicado. Las condiciones evaluadas en la extracción asistida por ultrasonido fueron volumen de solvente (mL): 50, 75 y 100; tiempo de sonicación (min): 5, 10 y 15; amplitud (%): 20, 40 y 60. Se utilizó un diseño de superficies de respuesta para obtener las condiciones de operación óptimas que lograran maximizar el rendimiento en antocianinas, compuestos fenólicos y capacidad antioxidante (medida con la técnica ABTS). La mezcla extractora consistió en una mezcla de alcohol etílico y ácido clorhídrico (0,1 N) en una proporción 85:15 (v/v), seleccionada a partir de estudios previos del grupo de investigación [13].

Se pesaron 10 g de pulpa de fruta y se la maceró con la mezcla extractora durante unos minutos. Posteriormente se colocó en un vaso doble camisa de 150 mL de capacidad (7 cm de diámetro exterior y 10 cm de alto) para someterlo a sonicación. El vaso fue conectado a un baño termostático modelo Rotovisco RV12 (HAAKE, Alemania). Se ajustó la temperatura del mismo a 12 ± 2 ºC de manera que la temperatura

del extracto alcanzara los 30 ± 1 ºC durante los primeros 3 min de sonicación, y permaneciera constante hasta cumplir los distintos tiempos de extracción evaluados. Se utilizó un equipo de ultrasonido Vibracell VCX-600 (Sonic Materials Inc., Estados Unidos) de alta intensidad y baja frecuencia (20 kHz, 600 Watts, 119 µm de amplitud de onda). Finalmente, los extractos fueron filtrados a vacío con papel Whatman (#1), se fraccionaron en 4 frascos de vidrio ámbar de 10 mL de capacidad, y se almacenaron a -80 ºC en un ultrafreezer MDF-U55V (Panasonic, Japón) hasta el momento de realizar las determinaciones. Para la evaluación de los tratamientos con ozono se utilizaron 10 extractos para cada tiempo de exposición al ozono y cada tiempo de almacenamiento.

2.4 Determinación del contenido de antocianinas, compuestos fenólicos y capacidad antioxidante

Antocianinas monoméricas totales (AT)

El contenido de AT fue determinado mediante la técnica de pH diferencial descripta por [15]. Los extractos fueron diluidos en frascos ámbar en una proporción 1:10 (v/v) en solución buffer de cloruro de potasio (0,025 M, pH 1,0) y en solución buffer de acetato de sodio (0,4 M, pH 4,5), agitados en un vórtex y, luego de 15 minutos de reposo a temperatura ambiente, se determinó la absorbancia a dos longitudes de onda, 510 y 700 nm, mediante un espectrofotómetro UV-VIS modelo V-630 (Jasco, Japón). El contenido de antocianinas fue expresado como miligramos de pelargonidina 3-glucósido (antocianina mayoritaria en frutillas) por cada 100 gramos de fruta (base seca). Las absorbancias de cada extracto se midieron por triplicado.

Compuestos fenólicos totales (FT)

El contenido de FT se determinó por el método colorimétrico de Folin-Ciocalteu utilizando la técnica modificada por [16]. En frascos de vidrio ámbar (5 mL) se colocaron 0,2 mL de extracto diluido (1/2,5) con 2,6 mL de agua bidestilada y 0,2 mL del reactivo Folin-Ciocalteu. Los frascos fueron agitados en vórtex y luego permanecieron 6 minutos en reposo al resguardo de la luz y a temperatura ambiente. Luego, se agregaron 2 mL de solución de carbonato de sodio 7 % (p/v), se agitó nuevamente en vórtex y se dejó reposar durante 90 minutos en las condiciones antes descriptas. Finalmente, se determinó la absorbancia de las muestras a 760 nm. Cada extracto se midió por duplicado. Los resultados se expresaron en mg equivalentes de ácido gálico presentes en 100 g de fruta (base seca) (mg EAG/100 g b.s.). La curva de calibración con ácido gálico se construyó a partir de 8 concentraciones diferentes en el rango 1 - 8 mg $AG.L^{-1}$.

Capacidad antioxidante (CA)

Para la evaluación del efecto de los tratamientos de ozono sobre la capacidad antioxidante se utilizaron dos metodologías: TEAC (capacidad antioxidante como equivalentes de Trolox) y ORAC (capacidad de absorción de radicales de oxígeno).

La determinación de CA mediante el método TEAC se realizó de acuerdo a la metodología descripta por [17] con ligeras modificaciones. En frascos de vidrio ámbar se colocaron 80 µL del extracto diluido (1/5) (v/v) con 7,92 mL de la solución de radical $ABTS^{\cdot+}$. Se agitó en vórtex y se incubó durante 2 h a 30 ºC en un baño termostático modelo Masson (Vicking, Argentina). Finalmente, se registró el decrecimiento en la intensidad de absorción del catión $ABTS^{\cdot+}$ debido a la interacción con compuestos donantes de hidrógeno o de electrones, midiendo la absorbancia a 734 nm. El blanco consistió en 80 µL de buffer fosfato pH 7,4 y 7,92 mL de la solución de radical $ABTS^{\cdot+}$. Los resultados se expresaron como mmol Trolox presentes en 100 g de fruta (base seca) (mmol Trolox/100 g b.s.). La CA se obtuvo mediante la comparación con curvas de calibración realizadas con Trolox, obtenidas a partir de 12 concentraciones diferentes en el rango 6-17 µM Trolox.

La determinación de CA mediante el método ORAC se realizó de acuerdo a la técnica descripta para la determinación de antioxidantes hidrofílicos [18] adaptada por [19]. Se utilizaron dos diluciones diferentes de los extractos, 1:160 (v/v) y 1:240 (v/v). La evolución de la fluorescencia durante el tiempo fue medida con un luminómetro Victor Multilabel 1420 (Perkin Elmer, Estados Unidos) sobre microplacas de poliestireno negras de 96 pocillos, de fondo plano y superficie sin tratamiento (Corming, Estados Unidos). En cada pocillo se colocaron 115 µL de fluoresceína ($8{,}16.10^{-5}$ mM) y 25 µL del extracto diluido. La mezcla se incubó bajo agitación a 37 ºC durante 10 minutos. Posteriormente, se adicionaron 60 µL de solución AAPH (153 mM), se agitó la placa durante 1 minuto y se comenzó inmediatamente con la medición manteniendo la temperatura fija en 37 ºC. Las lecturas en cada pocillo fueron registradas cada 40 s hasta cumplir un tiempo total de 66 minutos, utilizando filtros de emisión y excitación de 520 y 485 nm, respectivamente. El blanco consistió en utilizar 25 µL de buffer fosfato de potasio (75 mM, pH 7,4) en lugar del extracto. Los resultados fueron expresados como mmol equivalentes de Trolox presentes en 100 g de fruta (base seca) (mmol Trolox/100 g b.s.). La curva de calibración se construyó a partir de 6 concentraciones diferentes en el rango de 3,125 - 50 µM. Los diferentes extractos y patrones se midieron por duplicado.

2.5 Análisis estadístico

Los resultados fueron expresados como la media ± desviación estándar y fueron analizados mediante el programa Infostat v.2008 (Universidad Nacional de Córdoba, Argentina). Los datos fueron analizados mediante un ANOVA de dos factores (tratamiento y tiempo de almacenamiento). En caso de encontrarse diferencias significativas se aplicó un test de Tukey. Con el fin de determinar el grado de correlación entre el contenido de AT y FT con la capacidad antioxidante evaluada por TEAC y ORAC, se calcularon los coeficientes de correlación de Pearson. El nivel de confianza para todos los análisis se fijó en un 95 %. Para el análisis de superficies de respuesta y la optimización de las condiciones de extracción se utilizó el programa Statgraphics Centurion XVI (Statgraphics Technology Inc., Estados Unidos).

3 Resultados

3.1 Optimización de la extracción asistida por ultrasonido

En la Tabla 1 se presenta el diseño experimental utilizado para la optimización de las condiciones de extracción asistida por ultrasonido, estudiándose el efecto de tres variables independientes (volumen de solvente, tiempo y amplitud de sonicación) sobre tres variables respuesta (AT, FT, TEAC). Los resultados del modelo indicaron que el efecto principal del tiempo de sonicación en las tres variables respuesta evaluadas no resultó significativo. Sin embargo, para la capacidad antioxidante el término cuadrático de dicho factor si lo fue. Las interacciones Vsolvente -Tiempo, Amplitud - Tiempo y el término cuadrático del factor amplitud tampoco tuvieron un efecto significativo, por lo cual no fueron incluidos en el modelado y posterior optimización.

El modelo de regresión fue ajustado con las siguientes ecuaciones:

$$Y_{AT} = 28{,}681 + 1{,}054X_1 + 0{,}635X_2 + 0{,}023X_3 - 1{,}135X_1^2 - 1{,}384X_1X_2 + 0{,}256X_3^2 \quad (1)$$

$$Y_{FT} = 238{,}50 + 17{,}93X_1 + 13{,}50X_2 + 4{,}78X_3 + 3{,}60X_1^2 - 5{,}16X_1X_2 + 7{,}36X_3^2 \quad (2)$$

$$Y_{TEAC} = 4{,}045 + 0{,}043X_1 + 0{,}141X_2 + 0{,}077X_3 - 0{,}324X_1^2 - 0{,}044X_1X_2 - 0{,}188X_3^2 \quad (3)$$

Donde: X_1 representa el volumen de solvente, X_2 la amplitud y X_3 el tiempo de sonicación.

En la Figura 1 se presentan las superficies de respuesta obtenidas al representar las funciones del modelo. Para la representación gráfica de las variables de respuesta, el tiempo de sonicación se fijó en el valor optimizado, que resultó de 15 minutos. La optimización de las variables respuesta fue realizada mediante la maximización de la función "Deseabilidad", representada en la Figura 2.

Las condiciones de extracción optimizadas que maximizaron el rendimiento en AT, FT y TEAC resultaron: X_1 = 80 mL, X_2 = 60 %, X_3 = 15 min. La concentración de compuestos bioactivos y capacidad antioxidante predichos para las condiciones optimizadas fueron: AT: 29,51 mg Pg3/100g, FT: 266,27 mg AG/100g y TEAC: 4,07 mmol Trolox/100g; mientras que los valores observados resultaron: AT: 29,60 ± 0,70 mg Pg3/100g, FT: 265,61 ± 3,15 mg AG/100g y TEAC: 3,98 ± 0,10 mmol Trolox/100g. Puede observarse entonces que los resultados obtenidos utilizando las condiciones de extracción optimizadas son muy similares a los predichos por el modelo.

Tabla 1. Datos experimentales de las variables de respuesta obtenidos para las combinaciones de volumen de solvente (X_1), amplitud de sonicación (X_2) y tiempo de extracción (X_3).

	Variables independientes			Variables de respuesta		
Corrida	X_1 (mL)	X_2 (%)	X_3 (min)	AT (mg Pg3/100g)	FT (mg AG/100g)	TEAC (mmol Trolox/100g)
1	50	60	15	29,5 ± 2,9	247,4 ± 16,4	3,94 ± 0,12
2	50	40	15	27,9 ± 1,7	223,6 ± 3,7	3,80 ± 0,22
3	50	20	15	22,9 ± 2,3	231,4 ± 19,3	3,20 ± 0,06
4	75	60	15	28,7 ± 1,7	264,3 ± 8,6	3,73 ± 0,19
5	75	40	15	28,9 ± 3,0	252,4 ± 8,9	3,76 ± 0,12
6	75	20	15	28,9 ± 0,5	225,2 ± 2,1	3,68 ± 0,14
7	100	60	15	29,2 ± 2,0	264,2 ± 7,3	3,81 ± 0,21
8	100	40	15	29,4 ± 0,4	306,5 ± 16,0	3,89 ± 0,11
9	100	20	15	28,3 ± 1,6	262,3 ± 12,5	3,65 ± 0,08
10	50	60	10	28,4 ± 2,6	232,0 ± 15,3	3,68 ± 0,43
11	50	40	10	25,8 ± 1,9	235,9 ± 0,4	3,56 ± 0,22
12	50	20	10	25,3 ± 0,2	210,4 ± 2,8	3,39 ± 0,10
13	75	60	10	28,6 ± 0,7	281,0 ± 22,5	3,82 ± 0,18
14	75	40	10	28,8 ± 3,1	244,8 ± 3,3	3,65 ± 0,04
15	75	20	10	28,3 ± 0,6	225,2 ± 26,8	3,98 ± 0,14
16	100	60	10	27,0 ± 0,9	269,9 ± 20,2	3,72 ± 0,21
17	100	40	10	28,8 ± 0,8	264,1 ± 16,3	3,55 ± 0,23
18	100	20	10	28,3 ± 0,7	253,3 ± 7,0	3,61 ± 0,01
19	50	60	5	27,9 ± 3,2	247,4 ± 19,4	3,60 ± 0,17
20	50	40	5	28,0 ± 2,9	230,2 ± 12,5	3,45 ± 0,09
21	50	20	5	24,1 ± 0,1	203,4 ± 6,0	3,35 ± 0,05
22	75	60	5	29,3 ± 2,3	272,2 ± 10,8	3,98 ± 0,22
23	75	40	5	27,8 ± 1,3	247,7 ± 11,9	3,83 ± 0,18
24	75	20	5	28,2 ± 1,6	225,8 ± 3,6	3,35 ± 0,10
25	100	60	5	28,2 ± 1,4	262,0 ± 18,7	3,82 ± 0,15
26	100	40	5	28,7 ± 2,2	241,2 ± 12,1	3,36 ± 0,11
27	100	20	5	31,0 ± 4,5	260,9 ± 8,2	3,34 ± 0,15
28	75	40	10	31,0 ± 4,5	260,9 ± 8,2	3,34 ± 0,15
29	75	40	10	28,7 ± 2,1	241,1 ± 10,3	4,16 ± 0,58
30	75	40	10	31,3 ± 0,3	224,0 ± 13,1	4,15 ± 0,24
31	75	40	10	28,0 ± 1,7	210,2 ± 19,4	4,27 ± 0,51
32	75	40	10	28,1 ± 2,5	223,3 ± 11,9	4,49 ± 0,02
33	75	40	10	28,6 ± 1,5	227,6 ± 17,4	3,88 ± 0,03

34	75	40	10	30,2 ± 2,1	238,8 ± 20,2	4,46 ± 0,10
35	75	40	10	26,9 ± 0,3	211,7 ± 8,9	4,02 ± 0,43

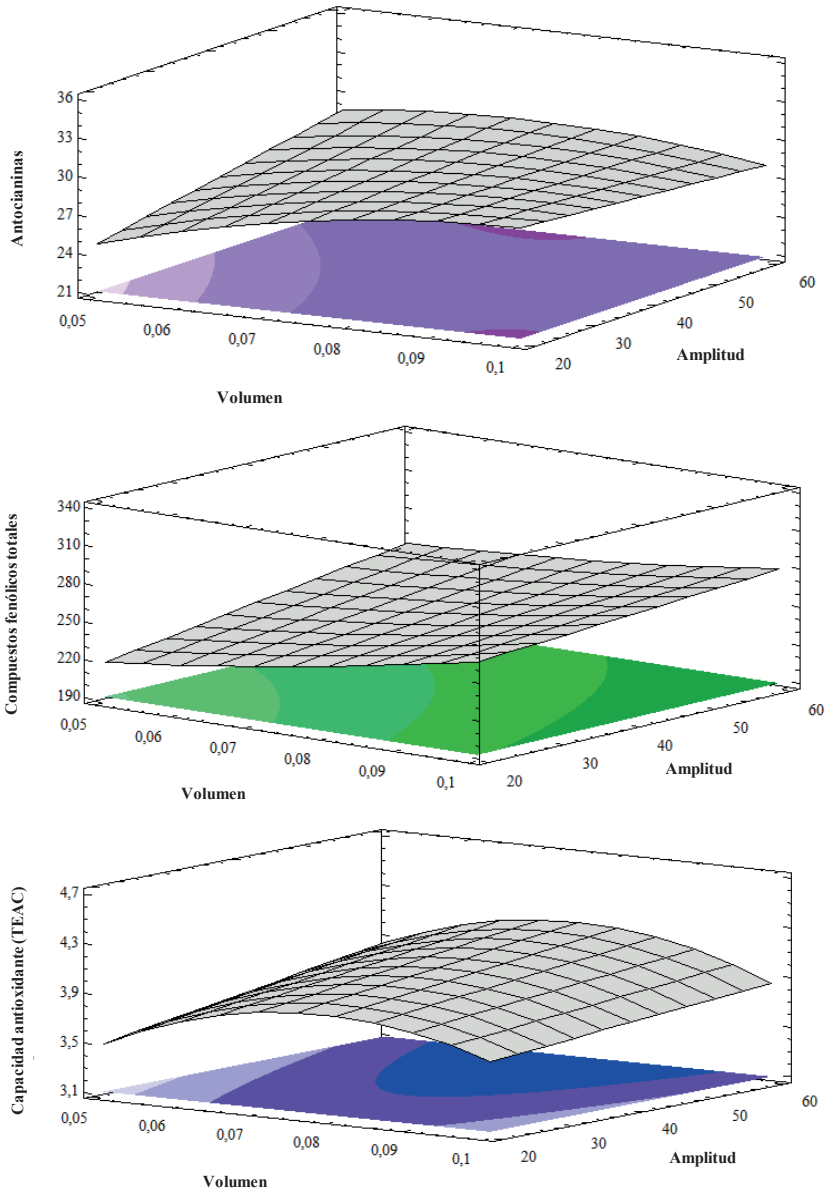

Fig.1. Superficies de respuesta correspondientes al contenido de antocianinas, compuestos fenólicos totales y capacidad antioxidante en función de la amplitud de sonicación y el volumen de solvente. Las gráficas corresponden a un tiempo de sonicación de 15 min.

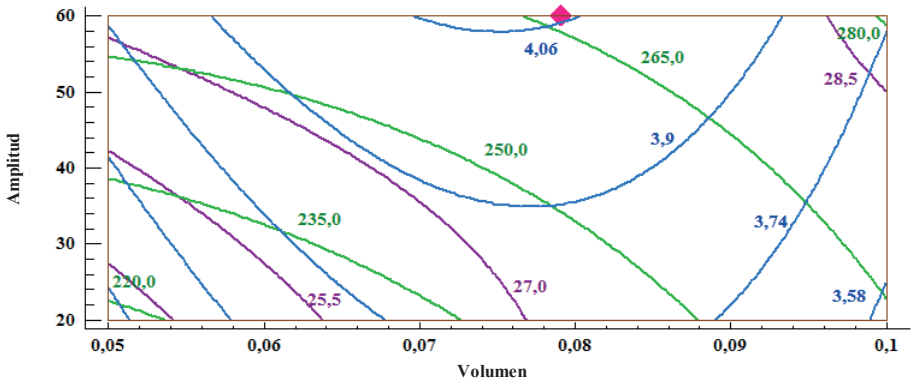

Fig.2. Gráfico de contornos de la función Deseabilidad. Contenido de antocianinas (▬), Contenido de compuestos fenólicos totales (▬), TEAC (▬), Máximo (♦). Las gráficas corresponden a un tiempo de sonicación de 15 min.

3.2 Efecto de los tratamientos de ozono en el contenido de antocianinas y compuestos fenólicos totales.

En la Tabla 2 se presentan los contenidos de antocianinas (AT) y compuestos fenólicos totales (FT) de frutillas control y ozonizadas durante el almacenamiento. El análisis estadístico indicó que la interacción entre los factores "tratamiento" y "tiempo de almacenamiento" resultó significativa ($F_{4,81}$ = 6,1, p<0,0002 y $F_{4,81}$ = 3,5, p<0,012, respectivamente. Los frutos control mostraron un incremento del contenido de AT durante el almacenamiento, que resultó significativo al día 8. En cuanto a los frutos ozonizados, las muestras tratadas durante 5 minutos no presentaron diferencias significativas en el contenido de AT durante el almacenamiento, al compararlas con el control. Por el contrario, los frutos tratados con ozono durante 15 minutos presentaron un contenido de AT significativamente menor que el control al día 8 de almacenamiento.

Los frutos control mostraron un incremento significativo en el contenido de FT al día 8 de almacenamiento, en concordancia con lo observado en el contenido de AT. El contenido de FT de los frutos ozonizados durante 5 minutos también aumentó significativamente al día 8, aunque sin presentar diferencias significativas respecto al control. Por otra parte, las muestras tratadas durante 15 minutos y almacenadas 8 días, mostraron un leve incremento no significativo en el contenido de FT a pesar de la disminución en el contenido de AT observado para ese mismo período de almacenamiento.

Tabla 2. Valores promedio y desviación estándar del contenido de antocianinas (AT), de fenoles totales (FT) y de capacidad antioxidante evaluada por ORAC y ABTS de frutillas control y ozonizadas durante el almacenamiento a 5 ± 1 ºC. Promedios seguidos de distinta letra minúscula difieren significativamente (p<0,05). (n = 10)

Parámetro	Tiempo de tratamiento (min)	Tiempo de almacenamiento (día)		
		0	4	8
AT (mg Pg3/100g b.s.)	0	224,7 ± 68,5 ^{a}	309,1 ± 49,9 ^{ab}	350,7 ± 88,7 ^{b}
	5	285,6 ± 43,9 ^{ab}	240,2 ± 72,9 ^{a}	271,4 ± 66,2 ^{ab}
	15	274,2 ± 75,6 ^{ab}	302,9 ± 75,0 ^{ab}	230,6 ± 46,8 ^{a}
FT (mg AG/100g b.s.)	0	1655,5 ± 234,2 ^{a}	1725,3 ± 174,0 ^{a}	2417,8 ± 297,9 ^{cd}
	5	1902,0 ± 187,0 ^{ab}	1649,3 ± 205,6 ^{a}	2589,6 ± 374,2 ^{d}
	15	1917,2 ± 399,6 ^{ab}	1689,5 ± 211,6 ^{a}	2201,9 ± 185,7 ^{bc}

Los resultados de la evaluación de la capacidad antioxidante determinada por las técnicas TEAC y ORAC se presentan en la Tabla 3. El análisis estadístico indicó que la interacción entre los factores "tratamiento" y "tiempo de almacenamiento" no fue significativa ($F_{4,81}$ = 1,76, p>0,1 y $F_{4,81}$ = 1,25, p>0,1, respectivamente). Al analizar el efecto principal de cada factor, en ambos casos se observó un efecto significativo del tiempo de almacenamiento sobre los valores TEAC y ORAC (p<0,05 y p<0,0001, respectivamente), mientras que el efecto principal del tratamiento con ozono no resultó significativo (p>0,05).

Se observó una disminución significativa en los valores TEAC al día 4, principalmente en los frutos ozonizados. En general, los valores TEAC tendieron a incrementarse hacia el final del almacenamiento (día 8), alcanzando valores que no difirieron significativamente con los correspondientes al día 0. Por el contrario, los resultados obtenidos mediante la técnica ORAC presentaron una tendencia diferente; tanto las muestras control como tratadas presentaron un incremento significativo de los valores ORAC a lo largo de todo el período de almacenamiento estudiado.

El análisis de correlación entre las variables medidas (Tabla 4), indicó que la correlación entre el contenido de AT y FT de las muestras no fue significativa (p>0,5), lo cual podría explicarse por la diferente tendencia observada entre la acumulación de AT y FT de los frutos ozonizados durante 15 minutos a lo largo del almacenamiento. Por otro lado, se observó una correlación significativa entre FT y los valores TEAC (r = 0,59), FT y los valores ORAC (r = 0,45), y AT y los valores ORAC (r = 0,39). Si bien los compuestos fenólicos, incluyendo las antocianinas, son compuestos abundantes en las frutillas y con conocida actividad antioxidante, la correlación observada entre AT y FT con la capacidad antioxidante fue débil, con coeficientes de correlación menores a 0,6.

Tabla 3. Valores promedio y desviación estándar del contenido de antocianinas de capacidad antioxidante evaluada por ORAC y ABTS de frutillas control y ozonizadas durante el almacenamiento a 5 ± 1 ºC. En una misma fila, los promedios seguidos de distinta letra mayúscula difieren significativamente ($p<0,05$). (n = 10)

Parámetro	Tiempo de tratamiento (min)	Tiempo de almacenamiento (día)		
		0	4	8
TEAC (mmol Trolox/100 g b.s.)	0	32,8 ± 3,1 ^{A}	31,8 ± 5,7 ^{B}	33,8 ± 5,1 ^{AB}
	5	36,1 ± 4,0 ^{A}	31,2 ± 5,6 ^{B}	36,6 ± 6,8 ^{AB}
	15	36,9 ± 4,9 ^{A}	32,1 ± 5,1 ^{B}	31,5 ± 4,0 ^{AB}
ORAC (mmolTrolox/100 g b.s.)	0	27,2 ± 5,9 ^{A}	42,5 ± 5,9 ^{B}	48,0 ± 4,2 ^{C}
	5	31,5 ± 7,5 ^{A}	36,1 ± 6,7 ^{B}	45,3 ± 4,5 ^{C}
	15	31,8 ± 1,9 ^{A}	43,5 ± 5,7 ^{B}	47,2 ± 10,9 ^{C}

Tabla 4. Resultados del análisis de correlación de Pearson para el contenido de antocianinas, compuestos fenólicos y capacidad antioxidante de frutos tratados y control durante el almacenamiento a 5 ± 1 ºC.

	AT	FT	TEAC	ORAC
AT	1,00	0,6739	0,6988	0,0040
FT	0,04	1,00	<0,0001	0,0006
TEAC	0,04	0,59	1,00	0,1902
ORAC	0,38	0,45	0,18	1,00

Resultados similares fueron reportados por [20,21]; mientras que por el contrario, otros autores [22] encontraron una correlación fuerte y positiva entre el contenido de AT y FT con los valores ORAC de frutillas almacenadas en refrigeración. Entre los factores que pueden afectar estas determinaciones, se encuentran las interacciones (aditivas o sinérgicas) entre distintos compuestos fenólicos de la fruta, como también con otros fitoquímicos; y la contribución a los valores ORAC de otros componentes como la vitamina C que no han sido evaluados en este trabajo. En particular, se ha reportado que esta vitamina representa entre el 9 y 15 % del valor ORAC [22].

Por otra parte, existen reportes acerca del incremento de las propiedades antioxidantes de diversas frutas como consecuencia de la exposición de los mismos al ozono [4,23,24]. Este incremento estaría asociado a respuestas de defensa desencadenadas por la exposición de los frutos a condiciones de estrés abiótico. Sin embargo, en las dosis ensayadas en este trabajo no se detectó un aumento en el potencial antioxidante de las frutillas.

4 Conclusiones

La acumulación de antocianinas en frutillas cv. Albion tratadas con ozono dependió de la dosis aplicada, resultando en una disminución significativa para el mayor tiempo de exposición al ozono, 15 min. Por el contrario, el contenido de compuestos fenólicos totales y la capacidad antioxidante no se vio afectada por ninguna de las dosis de ozono evaluadas. Por lo tanto, el tratamiento con ozono en fase acuosa durante 5 minutos podría ser una estrategia para extender la vida poscosecha de frutillas cv Albion sin afectar negativamente sus propiedades antioxidantes. Estudios complementarios en otros cultivares de frutillas contribuirían a una mejor caracterización del efecto del tratamiento y su potencial aplicación poscosecha.

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Desarrollo de yogur descremado deslactosado reducido en sacarosa mediante hidrólisis enzimática

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Resumen. Como Trabajo Final de la carrera Ingeniería en Alimentos, se buscó desarrollar un yogur descremado deslactosado, reducido en sacarosa a partir de la utilización de la enzima β-galactosidasa. Su formulación reducida en lactosa fue obtenida a partir de las experiencias prácticas llevadas a cabo en las instalaciones de la Facultad de Ingeniería, de la Universidad Nacional de Mar del Plata. Las materias primas requeridas fueron provistas por la Cooperativa de Trabajo Nuevo Amanecer Ltda. con quien se llevó a cabo el proyecto, mediante un convenio específico. Además de las prácticas de laboratorio, se realizaron cuatro instancias de análisis sensorial, con la colaboración de 10 panelistas entrenados. A partir de ellas se pudieron determinar diversos parámetros tales como: el tiempo de deslactosado mínimo requerido, el dulzor aportado por la hidrólisis enzimática, los endulzantes y espesantes a utilizar para obtener los atributos deseados y el rendimiento del proceso. Fue posible obtener dos formulaciones de similar aceptación sensorial entre sí.

Palabras clave: Yogur Deslactosado, Hidrólisis Enzimática, Yogur Reducido en Sacarosa.

1 Introducción

El presente trabajo se realizó en el marco de la materia Trabajo Final de Ingeniería en Alimentos (Facultad de Ingeniería, UNMDP) para obtener el título de grado de Ingeniera en Alimentos.

Desde el comienzo, la idea se centró en desarrollar un producto que satisficiera las necesidades de una porción de la población que eligiera un estilo de vida más saludable, buscando mantener la salud a partir de los alimentos elegidos para consumo cotidiano. Además, siempre se consideró interesante el hecho de facilitar el acceso a dichos alimentos. Es por ello que la idea de realizar un alimento saludable y accesible para toda la comunidad estuvo siempre presente.

Luego, se presentó la posibilidad de trabajar en convenio con una industria tradicional de la ciudad, como es la Cooperativa de Trabajo Nuevo Amanecer Ltda. cuyos orígenes se remontan al año 1939. La propuesta planteada por la empresa fue mejorar la formulación de un producto ya existente como es el yogur descremado saborizado. La mejora consistía en reducir la cantidad de sacarosa agregada mediante un tratamiento

enzimático de la materia prima, ya que se entendía que los consumidores que buscaban un producto descremado, también deseaban que fuera reducido en azúcares.

Para referirse al yogur según la normativa vigente es necesario recurrir al CAA [1] el cual establece que se entiende por yogur al producto adicionado o no de otras sustancias alimenticias, obtenidos por coagulación y disminución del pH de la leche (adicionada o no de otros productos lácteos) por fermentación láctica realizada con cultivos protosimbióticos de *Lactobacillus delbrueckii subsp. bulgaricus y Streptococcus salivarius subsp. thermophilus* a los que en forma complementaria pueden acompañar otras bacterias acidolácticas que, por su actividad, contribuyen a la determinación de las características del producto terminado. Estos microorganismos deben ser viables, activos y abundantes en el yogur durante su período de validez. La regulación también establece ciertos parámetros sensoriales, físico-químicos y microbiológicos a los que el yogur debe responder.

Los beneficios del consumo de yogur residen principalmente en el gran número de microorganismos vivos que el mismo contiene. Dichos microorganismos vivos hacen del yogur un alimento probiótico. Se define con este término a los organismos vivos que administrados en cantidades adecuadas proporcionan un beneficio saludable en el huésped [2]. Es así como los microorganismos generan beneficios mejorando el balance microbiano intestinal, lo que hace del yogur un alimento funcional, considerado un alimento que pueda proporcionar un beneficio a la salud, superior al de los nutrientes tradicionales que contiene, según la Academia Nacional de Ciencia de los Estados Unidos.

Se propone, entonces, como objetivo desarrollar un yogur descremado deslactosado firme sabor vainilla, con un menor contenido de sacarosa que el yogur descremado actual de la Cooperativa de Trabajo Nuevo Amanecer Ltda. a partir de la hidrólisis de la lactosa.

Para ello se parte de la hipótesis de que al hidrolizar el disacárido lactosa (proceso denominado deslactosado) que está presente en la leche (materia prima) utilizando la enzima β-galactosidasa se obtienen como productos glucosa y galactosa, los cuales son monosacáridos con un poder edulcorante mayor que el del disacárido mencionado.

2 Materiales y métodos

La materia prima base de todas las experiencias fue leche de vaca pasteurizada, homogeneizada y estandarizada con un contenido de materia grasa de 0,5 % p/p.

2.1 Experiencia 1: determinación del tiempo de deslactosado

El objetivo de la primera experiencia fue determinar el tiempo mínimo de hidrólisis de lactosa para alcanzar el máximo dulzor posible.

Para ello se adicionó la enzima Ha-Lactase 5200 de CHR HANSEN a una muestra de leche. La elección de la dosis de enzima (2000 NLU/L) y la temperatura de operación (40 °C) se realizó en base a los datos provistos por la ficha técnica [3]. En estas condiciones se ha observado una hidrólisis de entre 80 y 90 % en un tiempo de entre 2 y 4 h.

Por este motivo, se ensayó el deslactosado hasta 5 h, tomando muestras a diferentes tiempos.

Se decidió evaluar el dulzor alcanzado en cada tiempo de deslactosado a través de una evaluación sensorial con 10 jueces entrenados. No se realizó de manera analítica la determinación de lactosa, glucosa y galactosa ya que no se contaba con el instrumental necesario en el tiempo disponible.

La evaluación se basó en un test descriptivo, en el cual se evaluó la intensidad de sabor dulce utilizando una escala continua [4].

La experiencia se realizó como se detalla a continuación:

1. Se colocaron 5 L de leche en un recipiente y se llevó a T = 40 °C utilizando una olla y mechero con difusor.
2. Se agregaron 206 g de leche en polvo descremada y se agitó.
3. Se reservó una muestra de 500 mL de leche y se virtió en 2 recipientes de 250 mL (muestra t0).
4. A los 4,5 L restantes se les agregó 2 g (2000 NLU/L) de la enzima Ha-Lactase 5200 de CHR HANSEN y se agitó.
5. Se dividió el volumen total en 18 recipientes de 250 mL y se los colocó en baños termostáticos a 40 °C.
6. Se retiraron del baño termostático 3 muestras para cada uno de los tiempos de deslactosado (ver Tabla 1).

Tabla 1. Tiempos de deslactosado.

Muestra	Tiempo [h]
t1	0,5
t2	1
t3	2
t4	3
t5	4
t6	5

7. A medida que se retiraron las muestras del baño termostático a 40 °C, se las colocó en otro baño a 90 °C. Una vez que la temperatura en el interior del recipiente alcanzó 85 °C, se dejó durante 5 min para inactivar la enzima y se dejó templar a temperatura ambiente.
8. Se refrigeraron las muestras en heladera a 4 °C hasta su utilización en la evaluación sensorial.
9. Se realizó el análisis sensorial de las muestras t1, t2, t3, t4 y t5 para intensidad de sabor dulce, utilizando como anclajes las muestras t0 como muy baja y la muestra t6 como muy alta (ver Fig. 1).

4



Fig. 1. Escala de evaluación sensorial evaluando de 0 (muy baja) a 10, representando el anclaje "muy alto" el valor de 8.

Los resultados obtenidos se analizaron con ANOVA y posteriormente se utilizó el test de comparaciones múltiples de Tukey, en caso de hallarse diferencia significativa en las muestras. El nivel de significancia (α) utilizado fue de 0,05.

2.2 Experiencia 2: determinación del dulzor alcanzado con la hidrólisis

Los objetivos planteados para esta experiencia fueron:

- Analizar la intensidad de sabor dulce del yogur elaborado con leche deslactosada y con diferentes cantidades agregadas de sacarosa, a fin de determinar qué cantidad de sacarosa se puede reducir en la formulación original del yogur.
- Analizar la aceptabilidad sensorial de las diferentes muestras de yogur.
- Realizar un perfil de acidez del yogur durante la fermentación.

Para llevar a cabo esta experiencia se prepararon muestras de yogur con diferentes porcentajes de sacarosa respecto de la formulación original, las cuales fueron evaluadas por 10 jueces entrenados. La evaluación se basó en un test descriptivo, para el cual se utilizó una escala continua de intensidad de sabor dulce y un test de aceptabilidad sensorial, en el que se utilizó escala hedónica de 9 puntos [5].

La experiencia se realizó como se detalla a continuación:

1. Se colocaron 5 L de leche en un recipiente y se llevó a T = 40 °C utilizando una olla y mechero con difusor.
2. Se agregaron 206 g de leche en polvo descremada y se agitó.
3. Se reservaron 800 mL en un Erlenmeyer y se refrigeró a 4 °C (muestra A).
4. A los 4 L restantes en la olla se les agregó 1,6 g de enzima Ha-Lactase 5200 de CHR HANSEN y se agitó.
5. Se tomaron 4 Erlenmeyers, se vertieron 800 mL de la mezcla en cada uno de ellos y se colocaron en un baño termostático a 40 °C durante 2,5 h.
6. Se colocaron en todos los Erlenmeyers 4,7 g de estabilizante comercial E1[1], incluyendo la muestra A reservada en el paso 3.
7. Se agregaron distintas cantidades de sacarosa en cada uno de los Erlenmeyers como se indica en la Tabla 2:

[1] En todos los casos se omiten los nombres comerciales de los espesantes utilizados por acuerdo de confidencialidad con la Cooperativa de Trabajo Nuevo Amanecer Ltda.

Tabla 2. Contenido de sacarosa de las diferentes muestras.

Muestra	Contenido de sacarosa [g]	% de agregado de sacarosa con respecto a la formulación original
A	75,3	100
B	60,2	80
C	37,7	50
D	22,6	30
E	0	0

8. Se colocaron los recipientes en un baño termostático a 95 °C y una vez alcanzados los 85 °C dentro de los recipientes se esperaron 5 min.
9. Se retiraron las muestras del baño termostático y se las enfrió hasta 42 °C bajo un chorro de agua de red, con agitación continua.
10. Se disolvieron 50 U del fermento CHR HANSEN en 1 L de leche 0,5 % p/p de contenido graso, con agitación en un matraz.
11. Se agregaron 3 mL del fermento disuelto a cada muestra y se incubaron a 40-42 °C.
12. Se tomaron 10 mL de cada muestra con ayuda de una pipeta a diferentes tiempos (1 h, 1,5 h, 2 h, 2,5 h, 2,75 h, 3 h, 3,25 h) y se realizó una titulación con solución Dornic (0,09 N NaOH) utilizando fenolftaleína como indicador. Se registró el volumen gastado.
13. Al registrar un volumen gastado mayor a 6 mL (60 °D), se retiraron las muestras del baño termostático y se le agregaron 0,1 mL de esencia de vainilla.
14. Se colocaron 40 mL de cada muestra en 10 vasos plásticos (cada uno de 100 mL de capacidad) y se almacenaron a 4 °C hasta su utilización en la evaluación sensorial.
15. Se realizó una evaluación en la que se analizó la intensidad de sabor dulce de las muestras y la aceptabilidad sensorial de diferentes atributos de cada una de ellas (aroma, apariencia, color y brillo, textura en boca, sabor, sabor dulce y aceptabilidad global). Para el caso del análisis de la intensidad de sabor dulce se utilizaron como anclaje la muestra A como “alta” y la muestra E como “baja”.

La escala utilizada para la intensidad de sabor dulce es la presentada en la experiencia anterior (ver Fig. 1). A continuación, se muestra la escala hedónica de 9 puntos utilizada en la evaluación de los diferentes atributos de cada muestra (ver Fig. 2):



Fig. 2. Escala hedónica de 9 puntos utilizada para la evaluación sensorial de los atributos de las muestras.

2.3 Experiencia 3: elección del endulzante

En esta experiencia se evaluaron dos tipos de endulzantes para reemplazar una parte o la totalidad de la sacarosa, teniendo en cuenta que se debía cubrir el dulzor que aportaba el 80 % de sacarosa de la formulación original. Los endulzantes seleccionados fueron estevia y sucralosa, el primero por tratarse de un endulzante natural que no aporta cantidades significantes de calorías y el segundo por ser una halogenación del azúcar de mesa, que presenta un sabor similar al mismo, con un poder edulcorante 600 veces mayor, pero sin aporte calórico [6]. Para realizar la elección, se llevó a cabo una evaluación sensorial con 9 jueces entrenados. La evaluación se basó en una prueba hedónica para la cual se utilizó una escala de 9 puntos [7].

La experiencia se realizó como se detalla a continuación:

1. Se colocaron 4 L de leche en un recipiente y se llevó a T = 40 °C utilizando una olla y mechero con difusor.
2. Se agregaron 164,8 g de leche en polvo descremada y se agitó.
3. Se agregaron 1,6 g de enzima Ha-Lactase 5200 de CHR HANSEN y se agitó.
4. El recipiente con la mezcla se colocó en un baño termostático a 40 °C durante 2,5 h.
5. Se adicionaron 23,53 g de estabilizante comercial E1 a la mezcla, previamente disuelto en leche con 0,5 % p/p de contenido graso a 85 °C.
6. Se tomaron 5 Erlenmeyers y se colocaron 800 mL de la mezcla en cada uno.
7. Se agregaron distintas cantidades de endulzantes comerciales (solución líquida de esteviósidos 117 % p/v y sucralosa en polvo) en cada una de las muestras como se indica a continuación en la Tabla 3:

Tabla 3. Agregado de endulzantes (sacarosa, estevia y sucralosa) para las diferentes muestras.

Muestra	Agregado de sacarosa [g]	Agregado de estevia [g]	Agregado de sucralosa [g]
A	60,2	-	-
B	30,1	3,5	-
C	30,1	-	0,037
D	-	3,5	0,037
E	-	-	0,074

8. Las muestras se colocaron a 95 °C en un baño termostático y una vez alcanzados los 85 °C dentro de los recipientes se esperaron 5 min.
9. Las muestras se enfriaron hasta 42 °C bajo un chorro de agua de red, con agitación continua.
10. Se disolvieron 50 U del fermento CHR HANSEN en 1 L de leche 0,5 % p/p de contenido graso con agitación en un matraz.
11. Se agregaron 3 mL del fermento disuelto a cada muestra y se incubaron a 40-42 °C. El sobrante del fermento disuelto se congeló para utilizar en experiencias posteriores.

12. Utilizando una pipeta, se tomaron alícuotas de 10 mL de las muestras A y D (testigos) a diferentes tiempos (0 h, 0,5 h, 1 h, 1,5 h, 2 h, 2,5 h, 2,75 h, 3 h, 3,25 h) y se realizó medición de pH y titulación con solución Dornic (0,09 N NaOH) utilizando fenolftaleína como indicador. Se registró el volumen gastado.
13. Al registrar un volumen gastado mayor a 6 mL (60 °D), se retiraron las muestras del baño termostático y se le agregaron 0,1 mL de esencia de vainilla.
14. Se colocaron 40 mL de cada muestra en 9 vasos plásticos (cada uno de 100 mL de capacidad) y se almacenaron a 4 °C hasta su utilización en la evaluación sensorial.
15. Se realizó una evaluación sensorial en la que se analizó aceptabilidad de apariencia, textura en boca y sabor y aceptabilidad global, utilizando la escala presentada en la Fig. 2.

2.4 Experiencia 4: selección del espesante

En las experiencias anteriores se utilizó el espesante comercial E1, el cual fue provisto por la Cooperativa de Trabajo Nuevo Amanecer Ltda. Si bien se experimentó a nivel laboratorio en condiciones similares a las que se trabaja en la industria, no se logró la consistencia esperada para el yogur firme. Por ello se decidió realizar una cuarta experiencia para alcanzar la textura deseada, trabajando con otros espesantes o una combinación de ellos. La mezcla de endulzantes utilizada para esta experiencia en particular fue la de sacarosa con sucralosa, correspondiente a la muestra C de la experiencia 3, considerando que fue la que obtuvo mayor promedio en su puntaje de aceptabilidad.

La experiencia se realizó como se detalla a continuación:

1. Se colocaron 1,8 L de leche con en un recipiente y se llevó a T = 40 °C utilizando una olla y mechero con difusor.
2. Se agregaron 74,16 g de leche en polvo descremada y se agitó.
3. Se agregaron 0,72 g de enzima Ha-Lactase 5200 de CHR HANSEN y se agitó.
4. El recipiente con la mezcla se colocó en un baño termostático a 40 °C durante 2,5 h.
5. Se calentó la mezcla hasta 90 °C aproximadamente utilizando la misma olla y mechero con difusor. Se agregaron 67,73 g de sacarosa y 0,087 g de sucralosa en polvo. Se mezcló para homogeneizar con un batidor.
6. Se tomaron 6 Erlenmeyers y se colocaron 300 mL de la muestra en cada uno de ellos.
7. Se agregaron distintas cantidades de espesantes previamente disueltos (E1, E2 y E3) en cada uno de las muestras como se indica a continuación en la Tabla 4.

Tabla 4. Agregado de espesantes para las distintas muestras.

Muestra	E1 [g]	E2 [g]	E3 [g]	% en la formulación
A	-	1,96	-	0,6
B	-	2,62	-	0,8
C	-	3,28	-	1
D	-	-	0,98	0,3
E	1,63	-	0,33	0,5 de E1 y 0,1 de E3

8

F	1,63	-	0,65	0,5 de E1 y 0,2 de E3

8. Se colocaron las muestras en un baño termostático a 100 °C y una vez alcanzados los 95 °C dentro de los recipientes se esperaron 5 min.
9. Las muestras se enfriaron hasta 42 °C bajo un chorro de agua de red, con agitación continua.
10. Se colocó en cada muestra 1,2 mL del fermento descongelado conservado en la experiencia anterior y se incubaron a 40-42 °C.
11. Utilizando una pipeta, se tomaron alícuotas de 10 mL de las muestras a las 3 h y se realizó una titulación con solución Dornic (0,09 N NaOH) utilizando fenolftaleína como indicador. Se registró el volumen gastado.
12. Se retiraron las muestras del baño termostático y se le agregaron 0,03 mL de esencia de vainilla.
13. Se almacenaron las muestras a temperatura de refrigeración hasta realizar la evaluación sensorial.
14. La apariencia y la textura en boca fueron analizadas sensorialmente por 5 jueces entrenados en yogur, de manera grupal, comparando las muestras con el yogur firme descremado sabor vainilla de la Cooperativa de Trabajo Nuevo Amanecer Ltda.

2.5 Experiencia 5: determinación experimental del rendimiento

Para determinar el rendimiento experimental del yogur elaborado, se llevó a cabo el seguimiento de las muestras B y F en simultáneo a la realización de la Experiencia 4. Se registraron los pesos en distintas etapas del proceso y al final del mismo, es decir, finalizada la fermentación.

3 Resultados y discusión

3.1 Experiencia 1: determinación del tiempo de deslactosado

El test de ANOVA permitió determinar que al menos una muestra tenía diferencia significativa con respecto al resto, ya que F resultó mayor a F crítico, siendo estos valores 8,7 y 2,7 respectivamente. El test de Tukey permitió, mediante una comparación múltiple, identificar cuáles son las muestras entre las que existe diferencia significativa. Estos resultados se observan en el gráfico siguiente (ver Fig. 3).

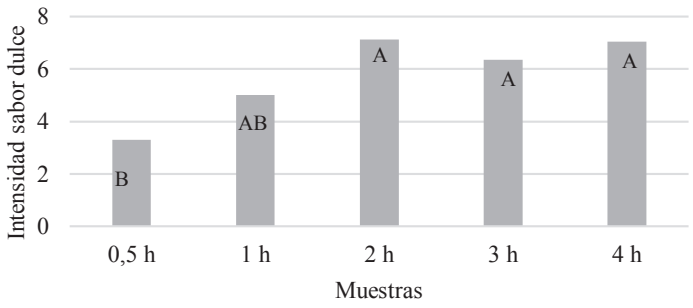

Fig. 3. Resultados de la intensidad de sabor dulce de leche descremada en función del tiempo de deslactosado con la enzima β-galactosidasa. Letras diferentes indican diferencias significativas en el sabor dulce debido al tiempo de deslactosado (Test de Tukey, α=0,05).

A partir de estos análisis fue posible determinar el tiempo mínimo de hidrólisis para alcanzar el máximo dulzor, siendo este de 2 h. Considerando que se trata de un proceso enzimático, el cual es susceptible a cambios en el medio, y que se pueden presentar variaciones tanto en la composición de la materia prima como en las condiciones del proceso, al tiempo de deslactosado determinado se le adicionó un 25 % más. De esta manera se estableció que esta etapa del proceso durara 2,5 h.

3.2 Experiencia 2: determinación del dulzor alcanzado con la hidrólisis

Perfil de acidez. Se presentan los presentan los valores de acidez obtenidos en las titulaciones realizadas (ver Fig. 4).

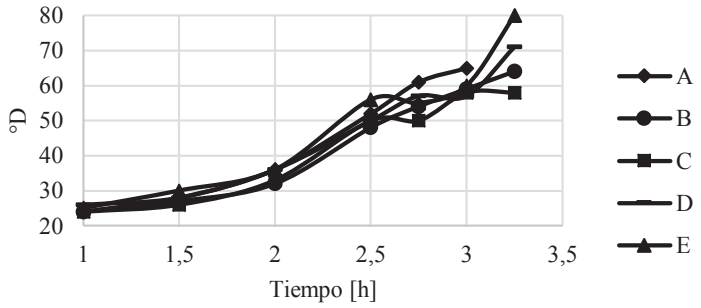

Fig. 4. Resultados obtenidos de la acidez del yogur durante la fermentación en función del tiempo.

En el gráfico de la Fig. 4 puede observarse que todas las muestras acidifican el medio de manera similar a lo largo del tiempo. Al ser el ácido láctico un producto del metabolismo de las BAL inoculadas, su concentración es proporcional a la población microbiana que se desarrolla en la etapa de fermentación. Esto puede relacionarse debido

a que la forma de las curvas obtenidas coincide con la curva típica de crecimiento microbiano, en la que se distinguen tres fases: latencia, exponencial y estacionaria [8].

Evaluación sensorial. El análisis de los datos recopilados en la evaluación sensorial se realizó de igual manera que en la experiencia 1 (utilizando el mismo nivel de significancia α=0,05) y los resultados se observan en el gráfico de la Fig. 5.

El test de ANOVA permitió determinar que al menos una muestra tenía diferencia significativa con respecto al resto, ya que F resultó mayor a F crítico, siendo estos valores 52,8 y 2,9 respectivamente. El test de Tukey permitió, mediante una comparación múltiple, identificar cuáles son las muestras entre las que existieron diferencias significativas.

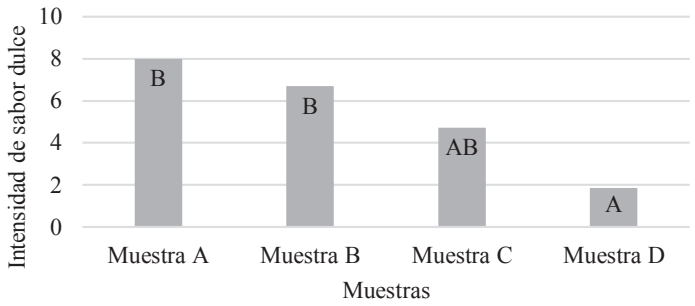

Fig. 5. Resultados de la intensidad de sabor dulce de yogur en función de la cantidad agregada de sacarosa. Letras diferentes indican diferencias significativas en el sabor dulce debido al agregado de sacarosa en distintas proporciones (Test de Tukey, α=0,05).

Como puede observarse, si bien la muestra A se utilizó como anclaje en 8 puntos, se decidió analizarla de igual manera que el resto. Esto es así ya que contenía la misma cantidad de sacarosa que el producto vigente de la Cooperativa de Trabajo Nuevo Amanecer Ltda. y, de esta manera, permitió realizar una comparación entre esta muestra y el resto, estableciendo o no diferencias significativas.

En el gráfico se observa que las muestras pueden ordenarse, según su intensidad de sabor dulce percibida por los panelistas, de manera coincidente con la cantidad de sacarosa agregada.

En cuanto al análisis estadístico, se puede observar que entre la muestra A y la muestra B no existieron diferencias significativas en la intensidad de sabor dulce percibida por los panelistas. De esta manera fue posible reducir la sacarosa agregada al yogur en un 20 %.

3.3 Experiencia 3: elección del endulzante

El análisis de los datos recopilados en la evaluación sensorial se realizó de igual manera que en la experiencia 1 (utilizando el mismo nivel de significancia α=0,05). El test de

ANOVA arrojó como resultado que no había diferencias significativas entre las muestras en ninguno de los atributos, por lo que no fue necesario realizar el test de Tukey. Considerando que una variación del endulzante afectaba principalmente el sabor y la aceptabilidad global, se muestran en la Fig. 6 y en la Fig. 7 los promedios de los puntajes obtenidos para cada muestra en estos atributos.

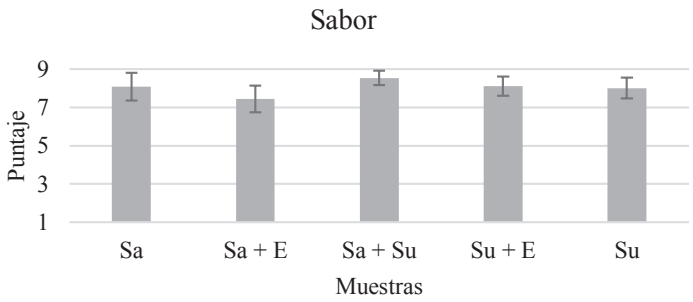

Fig. 6. Puntajes promedio obtenidos en la evaluación sensorial para la aceptabilidad del sabor (Sa: sacarosa, E: estevia, Su: sucralosa).

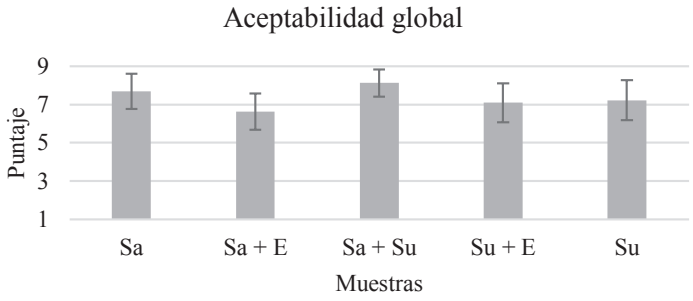

Fig. 7. Puntajes promedio obtenidos en la evaluación sensorial para la aceptabilidad global (Sa: sacarosa, E: estevia, Su: sucralosa).

Si bien no se observaron diferencias significativas en la aceptabilidad de los atributos ni en la aceptabilidad global de las muestras, cabe destacar que la de mayor puntaje fue la de sacarosa con sucralosa tanto en aceptabilidad del sabor como en aceptabilidad global.

Por otro lado, también puede notarse que todas las muestras obtuvieron puntajes mayores a 6, siendo el menor puntaje obtenido de aproximadamente 6,5, representando en la escala un punto medio entre “Me gusta poco” y “Me gusta”. Esto demostró que todas las muestras fueron aceptadas y, por lo tanto, la elección del endulzante o mezcla de endulzantes a utilizar en la formulación final dependía del concepto de producto que se deseaba o de su costo de producción.

3.4 Experiencia 4: selección del espesante

A partir de la evaluación y la comparación con el yogur firme descremado sabor vainilla utilizado como referencia, se determinó que la muestra B presentó mejor apariencia y textura en boca. La firmeza del coágulo fue similar a la del yogur de la Cooperativa de Trabajo Nuevo Amanecer Ltda., además, presentó un corte limpio acorde con la consistencia de un yogur firme.

3.5 Experiencia 5: determinación experimental del rendimiento

El cálculo del rendimiento total del proceso, el cual se obtiene a partir de la siguiente ecuación:

$$Rendimiento\ (\%) = \frac{masa\ final \cdot 100}{masa\ inicial} \quad (1)$$

Se tuvieron en cuenta los pesos iniciales y finales de las muestras B y F. A partir de dichos datos, se obtuvo el rendimiento para ambas muestras y, finalmente, el rendimiento promedio del proceso (ver Tabla 5).

Tabla 5. Masa inicial y final de las muestras B y F y Rendimiento del proceso.

	Muestra B	**Muestra F**
Masa inicial (g)	336,9	336,6
Masa final (g)	319,9	318,6
Rendimiento (%)	94,9	94,7
Rendimiento promedio (%)	95 %	

Como se puede observar, el rendimiento promedio resultó del 95 %. Este valor es similar al hallado en bibliografía, la cual indica que el rendimiento teórico del proceso es del 94 % [9]. Cabe destacar, que dicho valor está asociado a la elaboración a escala laboratorio del producto. Es así, que el mismo se ve afectado por el equipamiento, lo que sugiere que a escala industrial dicho valor podría verse modificado.

3.6 Formulaciones

Se presentan dos posibles formulaciones que fueron obtenidas para la fabricación de yogur descremado deslactosado firme sabor vainilla. La única diferencia que presentan entre sí está dada por la variación de uno de los endulzantes, ya que recibieron la misma aceptabilidad sensorial. Por un lado, la formulación A contiene como endulzantes sacarosa y sucralosa. Por otro lado, la formulación B presenta estevia y sucralosa. Ambas formulaciones se muestran a modo comparativo en la Tabla 6 donde, además, se detallan los componentes para las mismas. Vale aclarar que los porcentajes son en peso.

Tabla 6. Formulaciones del yogur descremado deslactosado.

Componentes	Formulación A (%)	Formulación B (%)
Leche descremada 0,5 % p/p	91,787	94,950
Leche en polvo descremada	3,676	3,803
Sacarosa	3,343	-
Estabilizante comercial E2	0,777	0,804
Inóculo	0,368	0,380
Enzima	0,036	0,037
Esencia de vainilla	0,009	0,010
Sucralosa	0,004	0,004
Estevia	-	0,012
Total	100,000	100,000

4 Conclusiones

Se logró obtener un yogur descremado firme sabor vainilla reducido en sacarosa. Dicho alimento puede ser considerado funcional debido a que contiene probióticos que ofrecen múltiples beneficios al consumidor.

A partir de la Experiencia 1 se determinó el tiempo óptimo de hidrólisis de la leche, para asegurar el máximo dulzor posible, en el menor tiempo involucrado. De esta manera, se llegó a un tiempo óptimo de deslactosado de 2,5 h. Por otro lado, en la Experiencia 2 se determinó que es posible reducir el contenido de sacarosa en el yogur en un 20 %, al utilizar la leche deslactosada según la Experiencia 1. Además, en cuanto al endulzante a utilizar, luego de probar diversas combinaciones en la Experiencia 3, se llegó a que la combinación sucralosa + sacarosa es la más aceptada. Sin embargo, no se observaron diferencias significativas entre las muestras, por lo que se concluye que todas las combinaciones evaluadas son factibles de utilizar en la formulación. Por último, en la Experiencia 4 se determinó el espesante a incluir en la formulación. De esta forma, se seleccionó el espesante E2 en una concentración de 0,8 %, debido a que otorga la apariencia y textura en boca deseadas.

En paralelo, se concluyó que el rendimiento del proceso fue del 95 %.

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Ultrastructural Damage and Mycotoxin Accumulation of *Aspergillus flavus*, *A. parasiticus* and *Fusarium verticillioides* as Affected by Flavonoids: a Comparative Study

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Abstract. In this study, the effects of naringin (NAR), neohesperidin (NEO) and quercetin (QUER), at 0.2 mM, were evidenced on the ultrastructure of *Aspergillus flavus*, *A. parasiticus* and *Fusarium verticillioides* by transmission electron microscopy images. Flavonoids were applied at 0.2 mM, alone or in combination affecting the structure of the cell wall, membranes and cytoplasm. In general, the cell wall lost rigidity and the cells appeared highly deformed with ruptured plasma membrane, regardless of the fungal species assayed.

The effect of flavonoids, in the same concentrations, on mycotoxins accumulation in maize at 0.98 aw, permitted the reduction of aflatoxins in a range from 82 to 99 % and a reduction up to 100% of fumonisins. The studied citrus flavonoids, which can be obtained from the citrus processing wastes, may provide an environmentally friendly alternative for decreasing aflatoxins and fumonisins accumulation in stored maize, replacing synthetic compounds.

Keywords: Mycotoxins · Maize · Flavonoids

1 Introduction

Mycotoxins are fungal toxic secondary metabolites encountered in food and feed. Aflatoxins (AFs) can be found in maize, among a variety of agricultural commodities and food products. AFs are produced by certain strains of *Aspergillus*, commonly *A. flavus*, *A. parasiticus* and *A. nomius* [1]. Aflatoxin B1 (AFB1), B2 (AFB2), G1 (AFG1) and

G2 (AFG2) are the most important, due to their occurrence in maize and to their mutagenic, carcinogenic, and hepatotoxic effects. Also, AFB1 has been classified as Group 1 (carcinogenic to humans) by the International Agency for Research on Cancer [1]. Main international markets set regulations for AFs in cereals and other foods, ranging between 1 and 12 μg/kg for AFB1, 4 and 15 μg/kg for AFB2, and 1 to 35 μg/kg for total AFs [2, 3].

Fumonisins (FBs) are mycotoxins with high occurrence in maize and its by-products [4]. FBs are mainly produced by *Fusarium verticillioides*, *F. proliferatum* and *F. fujikuroi*, among others [5]. Their production is stimulated by certain environmental conditions, being 25 °C and 0.98 a_w in the maximum accumulation range for *F. verticillioides* in maize [6]. Fumonisins B1, B2 and B3 (FB1, FB2 and FB3, respectively) are the analogues most frequently found in foods and those that exhibit the highest toxicity [5, 7] being associated with esophageal cancer and neural tube defects in humans [7]. FB1 is classified as a possible carcinogen within group 2B [8]. The maximum limits regarding FBs that were established by the EU according to the Commission Regulation N ° 1126/2007 [9] are 1000 μg/kg for corn and by-products used for human consumption, 800 μg/kg for breakfast cereals and 200 μg/kg for baby food, among others. The maximum values proposed by the Codex Alimentarius Comission and adopted by Argentina are 4000 μg/kg for corn grains and 2000 μg/kg for its by-products [10, 11].

It has been found that the highest co-occurrence of mycotoxins is given by AFs + FBs in cereals and derived products [12]. The study of mycotoxins in maize from different areas of Argentina between 1999 and 2010, showed that the co-occurrence of AFs + FBs was the most frequently detected combination, both at harvest and during maize storage [13].

Fungicides used to control post-harvest fungal diseases may promote fungal resistance, can leave persistent residues raising consumer concerns and cannot be used in organic or agroecological production systems, thus leading to a growing demand in favor of safe and effective natural preservatives [14].

Flavonoids are bioactive compounds from plants, with wide-ranging functions in plant metabolism. They can be classified into various sub-classes on the basis of the different oxidation level, unsaturation and substitution pattern. The flavonoids that occur in *Citrus* spp. belong to four groups: flavanones, flavones, flavonols and anthocyanins [15].

Approximately 50 % of the weight of the initial citrus fruit raw material remains as waste of the citrus processing industry, reaching more than 40 million tons worldwide [16]. Among all the possible applications, some flavonoids could be extracted at low cost from these agroindustrial by products and could represent an effective treatment against fungal contamination and also against mycotoxin accumulation in food products.

As an example, Naringin (NAR), neohesperidin (NEO), and hesperidin completely inhibited AFs accumulation by *A. flavus* when binary mixtures of these flavanones, extracted from citrus residues, were added to MEA, being the optimal mixture NAR 0.04 mM and NEO 0.2 mM [17].

The application of 0.8 mM of QUER to Czapek yeast extract agar reduced more than 50% ochratoxin A accumulation by *A. carbonarius* [18]. Moreover, QUER at a concentration of 0.37 mM in corn flour proved to dimminish *A. flavus* growth and aflatoxin production by suppressing MAPK signaling pathway involved in the AFs biosynthesis [19].

There are, to our knowledge, few studies available on the effect of flavonoids NAR, NEO and QUER, applied individually or in combination, on the ultrastructure of *A. flavus*, *A. parasiticus* and *F. verticillioides*. Recently, it has been shown that an optimal mixture composed of 0.39 mM NAR, 0.24 mM , and 0.40 mM QUER reduced from 85 % to 100 % the accumulation of AFs by *A. parasiticus* in maize adjusted to 0.95 and 0.98 a_w, with a deteriorative effect on the fungal ultrastructure [20]. Therefore, the aim of this study was to evaluate and compare the effect of two flavanones, NAR and NEO, and a flavonol, QUER, which can be extracted from the residuals of citrus industrialization, on the ultrastructure of *A. flavus*, *A. parasiticus* and *F. verticillioides* by transmission electron microscopy (TEM) and in the reduction of AFs and FBs accumulation in maize adjusted to 0.98 a_w, to be used as replacement of synthetic antifungal compounds.

2 Materials and Methods

2.1 Reagents and Chemicals

Sintorgan (Buenos Aires, Argentina) provided acetic acid (HAc), acetone, acetonitrile (ACN), glycerol, ethanol (EtOH), hexane and methanol (MeOH), HPLC grade, were purchased from; trifluoroacetic acid (TFA) from Tedia Company Inc. (OH, USA). Waters Milli-Q system was used to prepare HPLC quality water (Waters Associated, MA, USA). AFs and FBs standards were from Sigma (MO, USA). Malt extract broth (MEB), sodium hydroxide (NaOH), orthophosphoric acid, o-phthaldialdehyde, 2-mercaptoethanol, and tetraborate were purchased from Merck (Darmstadt, Germany). Culture medium MEA, and Tween 80 were purchased from Biokar (Beauvais, France).

2.2 Flavonoids

Immature grapefruit (*Citrus* × *paradisi*, Ruby Red cv.) and bitter orange fruit (*Citrus* × *aurantium*), which were discarded during juice processing, were processed to obtain the flavanones NAR and NEO, respectively [21]. The extraction was performed according to Salas [22], obtaining NAR 95 % pure and NEO 99 % pure. The flavonol QUER was purchased from Sigma (product no. 337951, purity of 95 %, Darmstadt, Germany).

2.3 Strains Selection

A. flavus, *A. parasiticus* and *F. verticillioides* species, belonging to the MICA culture collection of this research group, were selected according to their toxigenic capacity.

All of them were morphologically identified according taxon-specific diagnostic characters [23], and further subjected to PCR analysis in order to validate the morphological identification [20, 24] confirming the putative species. The strains were cultured in MEA slant tubes during 7 days. Then, tubes were filled with 10 ml of Tween 80 (0.02%) and the conidia were separated from the rest of the medium shaking 1 min in a vortex. The a_w of the suspension was adjusted with glycerol to a_w 0.98 as needed and its concentration was set to 5 10^6 conidia/ml. The volume of the inoculum used was 500 µl.

2.4 Transmission Electron Microscopy

For ultrastructure study flavonoids were added to MEB at 50 °C, previously adjusted to 0.98 a_w with glycerol. The treatments assayed were NAR, NEO or QUER individually applied at 0.2 mM, and the mixture composed of 0.2 mM NAR, 0.2 mM NEO and 0.2 mM QUER in combination. Tubes containing 10 ml of media were inoculated with 500 µL of conidia suspension and incubated at 25 °C for 5 d. Samples were prepared, fixed, and cut following traditional techniques [25]. Samples were observed in a Zeiss 109 transmission electron microscope (Carl Zeiss, Oberkochen, Germany) at 80 kV.

2.5 Mycotoxin assay

Substrate corresponding to 25 g of maize grains adjusted to 0.98 a_w, according to the maize sorption isotherms [26], was sterilized at 121 °C during 15 min using an autoclave (VZ, Buenos Aires, Argentina). Flavonoids were dissolved in 5 ml of EtOH and added to 100 ml water:glycerol 90:10 (w/w) (0.98 a_w), and stirred 5 min in an ultrasonic bath (Branson, MO, USA) at 50 °C until complete dissolution.

For each treatment, a total of 15 ml of the working solutions were added to maize. The appropriate flavonoid concentration were obtained in mmol/kg of maize (mM). Once the maize substrates were prepared and thoroughly shaken, they were inoculated and incubated during 14 days, in the case of *A. flavus* and *A. parasiticus*, or during 28 days in the case of *F. verticillioides*, both at 25 °C in sealed polyethylene bags. In order to maintain maize a_w level constant, open flasks containing water:glycerol solution where placed inside the bags.

Positive controls (maize inoculated following the same procedure but without adding flavonoids to the glycerol solution) and blank matrix (substrate without fungal inoculation) were also evaluated, by triplicate.

2.6 Quantification of Mycotoxins

Aflatoxins. The AFs quantification was performed according to Method 994.08 [27] using an Agilent 1100 series HPLC-FLD equipment (Agilent Technologies, CA, USA). For AFs extraction 25 g of maize were extracted with 100 ml ACN:H_2O (84:16 v/v). It was blended for 3 min at high speed (Osterizer, FL, USA) and filtered through Whatman paper no. 4 (Maidstone, UK). Then, 5 ml of the supernatant were passed through a solid-phase clean-up column MycoSep® 224 AflaZon (Romers, Getzersdorf, Austria). Subsequently, 1 ml was destined to AFs analysis. This extract was evaporated

under vacuum in a water bath at 60 °C until dryness, and then was reconstituted in 200 µl hexane. Derivatization was performed with 50 µl TFA, shaken for 30 s and after 5 min neutralized with 950 µl ACN:water (1:9, v/v). After that, 400 µl of the water phase was withdrawn. Silanized glass material was used throughout the procedure. For HPLC separation, a PhenoSphere-Next C18 reverse phase column (Phenomenex, CA, USA), 5 µm, 250 x 4.5 mm, was used. The mobile phase was water:ACN:MeOH (70:15:15, v/v/v), the flow rate was 1 ml/min, injection volume was 100 µl, and temperature fixed at 40° C. Fluorescence excitation and emission wavelengths were set at 360 nm and 440 nm, respectively. LOD and LOQ for AFs were 0.2 µg/kg and 0.4 µg/kg for AFB1, AFG1 and AFG2, respectively, and 0.3 µg/kg and 0.5 µg/kg for AFB2, respectively.

Fumonisins. Determination of FBs was performed according to the Official Method 995.15 [28]. Samples were blended for 3 min at high speed with 50 ml of MeOH:water 75:25 (v/v). The extract was filtered with Whatman paper no. 4, adjusted to pH 6 with 1 M NaOH, and centrifuged for 10 min at 2000 g (GELEC model G142, G-650 rotor, Buenos Aires, Argentina). Then, 10 ml of the extract were passed through quaternary amine solid phase extraction columns (CUQAX15Z, 500 mg; UCT, Bristol, PA, USA), previously conditioned with 5 ml of MeOH and 5 ml of MeOH:water 75:25 (v/v), consecutively added. Later they were washed with 5 ml MeOH:water 75:25 (v/v) and 5 ml of MeOH. FBs were then eluted with HAc:MeOH 1:99 (v/v) at a speed of 1 ml/min and the solvents were evaporated to dryness at 60 °C under a stream of nitrogen. The residue was resuspended in 500 µl of ACN:water 50:50 (v/v) and analyzed using Agilent 1100 series HPLC-FLD. FBs were derivatised online with a solution of o-phthaldialdehyde 2-mercaptoethanol (OPA-2-MCE). The injection program was set to mix 17 µl OPA-2-MCE, 20 µl sample and then 17 µl OPA-2-MCE prior to injection. Fluorescence excitation and emission wavelengths were set at 335 and 440 nm, respectively. An analytical LiChrospher RP-18 HPLC column of 250 × 4.0 mm × 5 µm (Merck, Darmstadt, Germany) was used. The isocratic mobile phase consisted of 1000 ml of 1 M sodium phosphate, 3348 ml of MeOH and 24 ml of orthophosphoric acid, adjusted to pH 3.3, with a flow rate of 1 ml/min and a column temperature of 30 °C. The limits of detection (LOD) were 2.3, 1.9 and 1.8 µg/kg for FB1, FB2 and FB3, respectively. The limits of quantification (LOQ) were 7.8, 6.2 and 5.8 µg/kg for FB1, FB2 and FB3 [29].

3 Results and Discussion

3.1 Alterations in Fungal Ultrastructure

The ultrastructure changes in *A. flavus*, *A. parasiticus* and *F. verticillioides* exposed to the different flavonoids were observed by TEM. Representative micrographs of the effects produced by the treatments in the different species are shown in Fig. 1.

The characteristic ultrastructure of untreated *A. flavus*, *A. parasiticus* and *F. verticillioides* is observed in Fig. 1A-C, respectively [20]. Cells of regular, turgid shapes can be noted, with normal cytoplasmic content and some distinguishable organelles.

Cell membranes appear intact. The cytoplasm is clearly surrounded by the cell wall and the fibrillar layer, both with high electronic density.

Treatment with 0.2 mM NAR produced severe damage to the structure of *A. flavus* cells (Fig. 1D). Disruption of the cell membrane and endomembrane system, and lysis of the cytoplasmic content, irregularities and rupture of cell walls and loss of content to the medium (black triangle), formation of numerous vesicles and detachment and agglomeration of the outer fibrillar layer were visualized. Similarly, treatment with 0.2 mM NAR induced a reduction in the thickness of the fibrillar layer and the cell wall in some areas of the *A. parasiticus* cells (Fig. 1E). The formation of multiple lipid bodies was striking, visualized both inside the cell and in the external zone (micrograph not shown). Disruption of the plasmalemma and other membranes occurred, with the formation of small vesicles and probably loss of permeability, and significant degradation of the cytoplasm. The same treatment altered the morphology of *F. verticillioides* cells, resulting in irregular shapes, undulating cell walls with invaginations or protrusions and, in some cases, walls appeared with lower electron density and some incipient disruption episodes (Fig. 1F). Disorganization of the cytoplasmic content and damage to the membrane of the nucleus and mitochondria were also observed in some cells.

A. flavus treated with 0.2 mM NEO (Fig. 1G) resulted in detachment and agglomeration of the fibrillar layer. The plasma membrane was damaged and detached from the irregular cell wall, without being able to contain the cytoplasm. Nuclei, mitochondria, and other organelles were observed with evident degradation. The treatment of *A. parasiticus* with 0.2 mM NEO (Fig. 1H) caused deformation of cell walls, detachment and rupture of the cell membrane, retraction of the cytoplasm (empty triangle) and formation of vesicles; lysis of the membranous organelles and the presence of large lipid bodies. The structure of the fibrillar layer was more similar to the control than in the case of the 0.2 mM NAR treatment. The application of 0.2 mM NEO to *F. verticillioides* produced some loss of rigidity of the cell wall, which appeared undulated, and deterioration in membranes with the consequent incipient disorganization of the cytoplasm, which exhibited numerous vesicles and good electron density (Fig. 1I).

The effects of 0.2 mM QUER, in the case of *A. flavus*, can be seen in Fig. 1J. Some cells were seen to be highly deformed, with irregular and folded cell wall, with deterioration of the cytoplasm. The plasma membrane appeared separated from the cell wall (empty triangle) and discontinuous. The cytoplasm was disorganized, with deteriorated material and the formation of small vesicles. The walls and the fibrillar layer were electronically very dense. The same treatment against *A. parasiticus*, induced agglutination and detachment of the fibrillar layer, formation of electronically dense grains in the inner part of the wall, disruption of the nuclear membrane and other organelles, and contraction and degradation of the cytoplasm (Fig. 1K). On the other hand, *F. verticillioides* treated with QUER 0.2 mM can be seen in Fig. 1L. Collapsed cells, an irregular cell wall, in some cases thicker compared to the control, and absence of cytoplasmic content in several cells were distinguished.

The treatment with the mixture of flavonoids (composed of 0.2 mM NAR, 0.2 mM NEO and 0.2 mM QUER) altered *A. flavus* cells (Fig. 1M). Although the external fibrillar layer was not absent, there were changes in its structure and detachment from the wall. The cell walls presented variable thickness, being broken in some cells (black

triangle). However, most of them did not appear folded. The cytoplasmic content was observed disorganized by the lysis of the membranes and the formation of vesicles, without distinguishing characteristic organelles. Cells without cytoplasmic content were also distinguished. On the other hand, when flavonoids were used in combination against *A. parasiticus* (Fig. 1N), cell contraction or deformation, along with membrane rupture and degradation were observed. The walls were folded and electronically very dense, indicating a specific effect of the mixture on its architecture. The fibrillar layer appeared adhered to the wall. Dispersed cytoplasmic content was noted inside, with formation of few vesicles. In the case of *F. verticillioides*, the treatment mainly altered the cell walls, as can be seen in the micrographs in Fig. 1O. In this case the combined use of NAR 0.2, NEO 0.2 and QUER 0.2 mM caused severe deformation, with cells folded several times on themselves, with invaginations and protuberances in the cell wall. The cells were agglutinated. Although the cytoplasm was disorganized, there is no indication that the cells have lost content. Some nuclei without membranes were present, also vacuoles and lipid bodies were differentiated.

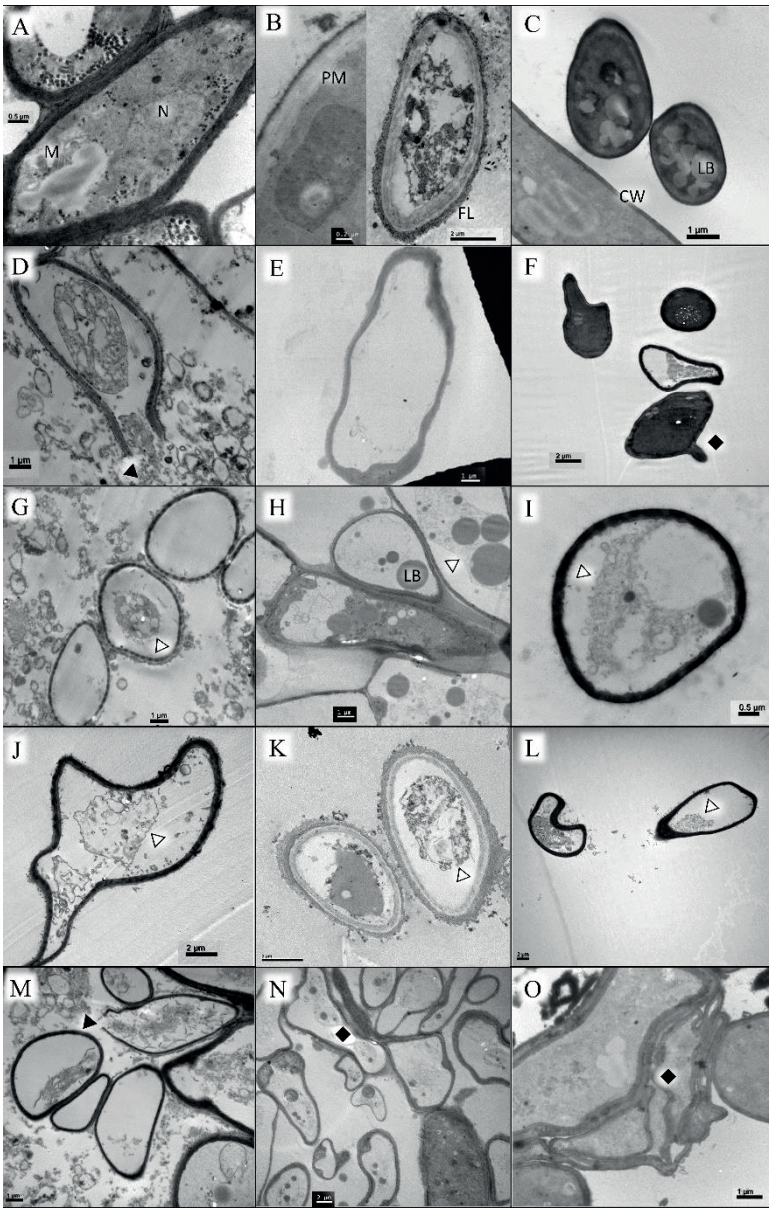

Fig. 1. Micrographies corresponding to *A. flavus* (first column), *A. parasiticus* (second column), and *F. verticillioides* (third column). Control (A-C), treatment with NAR 0.2 mM (D-F), NEO 0.2 mM (G-I), QUER 0.2 mM (J-L), and treated with mixture of NAR 0.2 mM, NEO 0.2 mM and QUER 0.2 mM (M-O). N: nuecleus, M: mitochondria, PM: plasmalemma, FL:fibrillary layer, CW: cell Wall, LB: lipid bodies. (▲): Cell wall disruption. (▷): Detachment and deterioration of plasmalemma. (◆): Unusual cell shrinkage.

The degeneration of various fungal organelles, the disorganization and breakage of lipid bilayer membranes and the changes in cell walls observed by TEM indicated that flavonoids targeted multiple sites of these three species cellular ultrastructure. These alterations can be compared to the morphological damages produced in *A. parasiticus* when applying Akacid®plus, which is a synthetic fungicide, eventually leading to cell death [30]. Also these alterations are similar to those caused by the synthetic antifungals fludioxonil + metalaxyl-M typically applied in maize against *F. verticillioides* [31]. The application of 1.5 mg/L of these compounds generated the loss of the characteristic structure of the hyphae, which appeared contracted with defects on the cell wall, evidenced by scanning electron microscopy. Although treatment with fludioxonil + metalaxyl-M interfered in *F. verticillioides* mycelial morphology and sporulation, it also significantly raised FB1 accumulation levels. The morphological effects of natural compounds, such as *Zingiber officinale* essential oil, on microconidia of *F. verticillioides* presented reduction of turgor, loss of membrane integrity and inhibition of ergosterol production and reduction of FB1 and FB2 accumulation *in vitro* [32].

Hydroxyl (-OH) groups and double bonds, present in the studied flavonoids, could be responsible of the antimicrobial activity, as these groups could promote the delocalization of electrons that reduce the gradient across the cytoplasmic membrane of microbial cells [33] possibly due to the interactions with the hydrophilic region of phospholipids in the cell membrane and the eventual penetration to the hydrophobic nucleus, producing alterations in the fluidity of the membranes, evidencing an increase in ion flux and relative conductivity [34]. In the case of *Candida albicans* treated with 0.03 mM QUER, Mg^{2+} accumulation increased due to the disruption of mitochondrial membranes, leading to an disarrange of antioxidant systems, subsequently resulting in DNA fragmentation [35]. In this work the application of flavonoids induced alterations in the cell wall in addition to those in the plasma membrane and the endomembrane systems. Fungal cell walls are composed of chitin microfibrils inter chained by hydrogen bonding, glucan chains (principally β-glucan) and modified glycoproteins with N-linked and O-linked oligosaccharides [36]. These components provide the cell wall with mechanical strength. As seen in TEM, flavonoids QUER, NAR and NEO affected the macromolecular crosslinking of the walls, which became pliant, affecting cell osmotic stability and favoring the malformation of the cells.

Despite the fact that different media were used to assess ultrastructure damage and mycotoxin accumulation so that a direct relationship between both effects is not possible, the individual flavonoids evidently altered the structure and promoted the formation of vesicles due to the disorganization and disruption of the membranes. Fewer organelles remained, and scarce cytoplasmic content was evidenced when the flavonoid mixture was applied (Fig. 1M-O).

3.2 Effect on Mycotoxin Accumulation

After incubation time, AFs and FBs accumulation in maize were analyzed. The accumulation of AFs by *A. flavus* control reached 1578 ± 1214 µg/kg for AFB1 and 74 ± 68 µg/kg for AFB2. In the case of *A. parasiticus* AFs accumulation levels were 53557 ± 47880 µg/kg, 145960 ± 130086 µg/kg, 2965 ± 2592 µg/kg, and 9132 ± 8575 µg/kg

for AFB1, AFG1, AFB2 and AFG2, respectively. Regarding FBs accumulation by *F. verticillioides* concentration of FB1, FB2 and FB3 reached 2807 ± 1356 µg/kg 229 ± 330 µg/kg 1687 ± 191 µg/kg, respectively. All strains were considered highly mycotoxigenic, surpassing the maximum levels set by the European Commission regulations. The percentage decrease in concentration of these mycotoxins in maize, produced by the addition of the studied flavonoids, are shown in Table 1.

Table 1. Relative pergentage reduction of the different mycotoxins studied in maize at 0.98 a_w. (*) Accumulation was increased.

Treatment	AFs reduction (%)						FBs reduction (%)		
	A. flavus		*A. parasiticus*				*F. verticillioides*		
	AFB1	AFB2	AFB1	AFG1	AFB2	AFG2	FB1	FB2	FB3
mixture	95 ± 5	99 ± 1	90 ± 2	92 ± 1	94 ± 1	97 ± 0	58 ± 8	36 ± 26	97 ± 3
NAR	87	94	95	94	98	98	29	*	84
NEO	90	98	95	96	96	98	90	100	100
QUER	82	95	94	95	97	98	69	88	82

AFs reduction surpassed the 80% in the case of *A. flavus* and *A. parasiticus*, regardless of the flavonoids used, alone or in combination.

Based on the data corresponding to the *A. flavus* transcriptome, it has been shown that certain genes necessary for the development of its conidia and mycelia are down regulated when QUER is applied to the culture medium [37]. Likewise, some of the transcription factors related to sexual development and to specific conidiation proteins were also decreased. Furthermore, the redox state in *A. flavus* mycelia has been shown to be closely related to AFs production. QUER proved to be effective in reducing the level of reactive oxygen species (ROS) in *A. flavus*, therefore, a mechanism of QUER effect on mycotoxins could be the depletion of intracellular ROS levels [38].

The functional importance of vesicles and vacuoles in the biosynthesis and export of fungal secondary metabolites in *A. parasiticus* has been demonstrated in the case of aflatoxins, as its production is completed in vesicles and vacuoles. These membranous organelles, endosomes or aflatoxisomes, participate in compartmentalization and export of AFs to the growth medium, potentially by exocytosis [39]. The metabolic pathways of these secondary metabolites, as well as the proteins involved in the response to stress factors would be present in the cell fraction corresponding to endosomes, transport vesicles and vacuoles [40]. Then, the low production of AFs due to treatment with flavonoids would be explained, at least partially, by a very severe alteration of these structures of the fungal cells [20].

Regarding *F. verticillioides*, evidence about the mechanisms of action of flavonoids on FBs concentration is scarce. Although some authors may link the decrease in FBs production with growth alterations, in some cases, as can be seen in this work, hyphae malformation and distortion does not lead to the reduction in FBs accumulation [41]. The application of NAR increased 75% FB2 accumulation in maize, in spite of the ultrastructure alterations evidenced in Fig. 1F.

4 Conclusions

Flavonoids produced severe alterations on *A. flavus*, *A. parasiticus*, and *F. verticillioides* ultrastructure and reduced the mycotoxin accumulation by these species. In general, the application of flavonoids NAR, NEO or QUER resulted in cell wall alterations, degradation of cytoplasm and depletion of plasmalemma and other membranes, with a reduction effect in mycotoxins accumulation, possibly due to the effect in the cell wall ductility with loss of osmotic stability and to the disarrangement of antioxidant systems.

AFs produced by *A. flavus* and *A. parasiticus* highly toxigenic strains were efficiently reduced by all applied treatments. FBs by *F. verticillioides* were best inhibited from 90 % to 100% with NEO 0.2 mM. Conversely, NAR 0.2 mM increased FB2 accumulation.

The flavonoid mixture composed of NAR, NEO and QUER reduced the mycotoxins produced by these three species. It would be interesting to find an optimal mixture that achieve total mycotoxin inhibition. These flavonoids may represent environmentally friendly additives against mycotoxins, as they can be extracted from the wastes of the citrus industrialization, being an alternative strategy to replace chemical additives for stored maize.

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Efecto del salado sobre las propiedades reológicas y la estructura de filetes de merluza (*Merluccius hubbsi*) utilizando diferentes métodos

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Resumen. El objetivo del presente estudio fue investigar el efecto de los diferentes procedimientos de salado sobre las características reológicas y la microestructura de filetes de merluza. Los tres procedimientos salado seco (SS), húmedo (SH) y mixto (SM) presentaron un aumento en el módulo elástico y de pérdida con el incremento del tiempo de salado. En todos los casos, G' excedió los valores G´´, indicando un comportamiento sólido predominante. Los valores de G' para SH con 48 h de salado fueron similares a los alcanzados con 8 h de SS y SM. En términos de prueba de barrido de temperatura, para la merluza fresca, el primer pico en G´ se asoció con la desnaturalización de la miosina, mientras que la actina fue más resistente al aumento del contenido de sal en el músculo. En muestras saladas, la miosina y la actina convergieron a un mismo pico de temperatura de desnaturalización (Td). Los métodos SS y SM presentaron una Td levemente mayor, mientras que las muestras SH mostraron una Td más cercana a la merluza fresca. Las micrografías SEM revelaron que las diferencias encontradas entre métodos se deben a los cambios conformacionales sobre las proteínas miofibrilares y sobre los componentes estructurales como el colágeno del tejido conectivo, directamente relacionadas con el contenido de agua y sal. Los efectos del salado seco fueron más relevantes en comparación con la inmersión en salmuera ya que SS mostró los valores más altos de z_{NaCl} y el SH presentó los menores.

Palabras clave: Salado, *Merluccius hubbsi*, Propiedades reológicas, Microestructura, Proteínas miofibrilares.

1 Introducción

Merluccius hubbsi es la especie dominante en Argentina en términos de biomasa y habita desde Cabo Frío, en Brasil (22° S), hasta el sur de Argentina (55° S), en profundidades entre 50 y 500 m [1]. Es la base de la industria pesquera del país y la especie más importante en el consumo interno. El 90 % de la producción es exportada fundamentalmente como filete congelado y descabezada y eviscerada (H&G). Los alimentos de origen marino son actualmente aceptados como un alimento esencial para el ser humano

debido a sus proteínas de alto valor biológico, ácidos grasos poliinsaturados, principalmente omega-3 y otros nutrientes, como minerales, oligoelementos y vitaminas [2]. Las proteínas del músculo de los peces se pueden dividir en tres grupos: proteínas miofibrilares (actina, miosina, tropomiosina y actomiosina), que constituyen el 70-80 % del contenido total; proteínas sarcoplasmáticas (mioalbúmina, globulina y enzimas), fracción que constituye el 25-30 % del total de proteínas; y, proteínas del tejido conectivo (colágeno), que representan entre 3-10 % [3].

Diferentes métodos de salado han sido utilizados para conservar los alimentos desde el Antiguo Egipto [4]. Para el salado de pescado, existen tres procedimientos: salado húmedo, salado seco y una combinación de ambos. En el salado húmedo, los filetes se sumergen en una solución de sal y agua, mientras que en el salado seco el pescado se apila en capas alternas de pescado y sal. El pescado absorbe sal, mientras que el líquido que difunde desde el músculo se permite que drene. El procedimiento de salado mixto es similar al procedimiento de salado seco, pero en recipientes cerrados. La calidad y los cambios estructurales de las proteínas en los productos salados están influenciadas por el método utilizado. Las proteínas sufren desnaturalización, siendo la cadena pesada de miosina más susceptible a la desnaturalización por salado fuerte [5].

La textura es un parámetro esencial en los alimentos que influye directamente sobre la aceptación de los consumidores. Las propiedades texturales de un alimento son el grupo de características que dependen de sus elementos estructurales y se relacionan con la deformación, desintegración y flujo por la aplicación de una fuerza. Una propiedad importante del alimento que se asocia con la textura es su comportamiento reológico. Estas propiedades están íntimamente relacionadas con las propiedades fisicoquímicas y funcionales de los constituyentes de un sistema alimenticio, así como, las variables de operación que se aplican en las diferentes etapas del proceso [6].

El efecto del salado sobre las propiedades reológicas y estructura del tejido muscular de mamíferos es bien conocido [7]. Sin embargo, se encuentra disponible muy poca información relacionada con este efecto en proteínas de pescado. No existen estudios sobre los cambios reológicos provocados por el salado en *Merluccius hubbsi*. Así, la merluza salada podría ser una alternativa para incrementar el valor agregado de los productos pesqueros y diversificar la oferta de productos del mar.

En este contexto, el objetivo del presente trabajo fue estudiar el efecto del salado sobre las características reológicas de filetes de merluza salados por diferentes métodos y comprender sus cambios estructurales mediante imágenes de microscopía electrónica.

2 Materiales y Métodos

2.1 Materia prima

Se trabajó con filetes de merluza (*Merluccius hubbsi*) frescos, sin piel, provistos por una pescadería local (Mar del Plata, Buenos Aires, Argentina). Los filetes se obtuvieron de forma manual y éstos se cortaron en trozos de 100x50x10 mm. Se mantuvieron a 4 ± 1 °C hasta el momento del procesamiento.

2.2 Procedimientos de salado

Los filetes de merluza fueron salados a 4 ± 1 °C siguiendo tres procedimientos. Inmersión en salmuera saturada (**SH**): solución con sal entrefina comercial (CELUSAL, Buenos Aires, Argentina) y agua corriente (26 % p/p NaCl, relación pescado:salmuera 1:10). Salado seco (**SS**): capas alternas de pescado y sal se colocaron uniformemente en un recipiente con drenaje, empezando y terminando con una capa de sal. Salado mixto (**SM**): se colocaron de la misma forma capas de pescado y sal en un recipiente sin drenaje. Muestras con 0, 2, 8, 24 y 48 h de salado fueron destinadas para las distintas determinaciones experimentales. Muestras extraídas a 0,5 y 4 h de salado fueron diseñadas adicionalmente para microscopía electrónica con el objetivo de evidenciar más claramente los efectos de salting-in y salting-out que ocurren en el músculo a fuerzas iónicas por debajo y por encima de 1 molar (M), respectivamente [8].

2.3 Determinaciones fisicoquímicas

Las muestras del salado húmedo una vez extraídas se dejaron escurrir y se secaron con papel absorbente, mientras que los trozos con salados seco y mixto fueron sumergidos previamente en salmuera saturada por 30 segundos para retirar el exceso de sal de la superficie. A continuación, se sometieron a un homogeneizado con procesadora (MOULINEX, Buenos Aires, Argentina) para las determinaciones fisicoquímicas. El contenido de agua (x_w) se realizó por secado en estufa a 105 ± 2 °C hasta peso constante [9]. Contenido de cenizas a partir de la calcinación del residuo seco en mufla a 500 ± 5 °C hasta cenizas blancas (8 h) [9]. Determinación de NaCl (x_{NaCl}) mediante la técnica de Mohr [10] partiendo de las cenizas. Las determinaciones de contenido de agua, cenizas y NaCl fueron realizadas por triplicado. Asimismo, se calculó la concentración de NaCl en fase líquida (z_{NaCl}) con la **Ecuación (1)** [11]:

$$z_{NaCl} = \frac{X_{NaCl}}{X_w + X_{NaCl}} \qquad \text{Ec. (1)}$$

2.4 Ensayos oscilatorios

Se realizó un barrido de frecuencias para evaluar las propiedades reológicas del músculo de merluza fresca y salada, con un reómetro Anton Paar (Physica MCR 301, Ostfildern, Alemania). Para ello, se determinó primeramente el rango viscoelástico lineal (RVL) con un barrido de amplitud con control de la deformación de cizalla (BA CDC). Se fijó la frecuencia angular en 1 s^{-1}, barriendo la amplitud de deformación entre 0,001-10 %. Dentro del RVL, se realizó el barrido de frecuencias para determinar los espectros mecánicos (G', G" y η*). Se utilizó una platina de 25 mm de diámetro, un rango de frecuencia angular de 0,5-50 s^{-1} y la temperatura de trabajo fue de 20 °C. Para evitar deslizamientos de la muestra y errores en las mediciones asociados a cambios en el volumen (contracción de las fibras musculares), en todos los casos se aplicó un esfuerzo normal de 0,5 N [12]. Las muestras fueron cortadas paralelo a la dirección de

las fibras musculares utilizando un sacabocado cilíndrico de igual diámetro que la platina. Adicionalmente, se realizaron ensayos de termo-reología (1 $\mathbf{s}^{-1}$; 0,05 % de deformación) en el rango de temperatura de 20-90 °C, velocidad de calentamiento 3 °C/min.

2.5 Microscopía SEM

Los cambios en la microestructura del tejido de merluza durante el salado fueron evaluados a través de micrografías de cortes del filete longitudinales. Para ello, cubos (10 mm) de merluza fresca y salada fueron sumergidos en N_2 líquido y liofilizados (3 días, 1 Pa) (Boyikang Laboratory Instruments Co., Ltd, Beijing, China). Los cubos se colocaron en portaobjetos SEM y se metalizaron con oro (100 Å de espesor). Las muestras se observaron en un microscopio electrónico de barrido (JSM 6460 LV, JOEL, Japón) equipado con un sistema de procesamiento de datos a un voltaje de 15 kV.

2.6 Análisis estadístico

Se utilizó el análisis de varianza de dos factores (ANOVA) para establecer la presencia o ausencia de diferencias significativas en los valores de x_w, x_{NaCl} y z_{NaCl} de los filetes de merluza, según los factores "método de salado" y "tiempo" con un nivel de significación de $p < 0,05$ (Infostat v 2009, Universidad Nacional de Córdoba, Argentina).

3 Resultados y Discusiones

3.1 Parámetros fisicoquímicos

El contenido de humedad, cloruro de sodio y cloruro de sodio en fase líquida del pescado para filetes de merluza fresca y salada, se presentan en la **Tabla 1**.

Para los tres procedimientos de salado estudiados, z_{NaCl} en merluza mostró un aumento con el tiempo de salado. Los análisis de varianza mostraron diferencia significativa en la interacción entre el tiempo y el método de salado ($p < 0,05$). Luego de 2 h, las muestras SS presentaron valores de z_{NaCl} significativamente diferentes con respecto a las muestras SM y SH. Las muestras SS y SM no mostraron diferencias significativas en los valores finales de z_{NaCl}. Para 48 h, el SS mostró los valores más altos de z_{NaCl} y el SH presentó los menores. Para tiempos de salado cortos (< 8 h), el comportamiento de SM fue similar al de muestras SH, pero para tiempos de salado más prolongados, los valores de z_{NaCl} de muestras SM se acercaron a los valores de SS. Las diferencias observadas en los valores de z_{NaCl} entre los diferentes métodos podrían atribuirse a diferencias en las fuerzas impulsoras presentes en cada sistema. Barat et al. [11], [13] observaron efectos similares con diferentes concentraciones de salmuera durante el salado de bacalao (*Gadus morhua*).

Tabla 1. Humedad promedio (x_w), cloruro de sodio (x_{NaCl}), cloruro de sodio en fase líquida (z_{NaCl}) y desviación estándar para 0, 2, 8, 24 y 48 h de SH, SM y SS de filetes de merluza.

	t (h)	x_w (g_{agua}/g_{mh})	x_{NaCl} (g_{sal}/g_{mh})	z_{NaCl} ($g_{sal}/g_{sal+agua}$)
Fresca	0	$0,798 \pm 0,003^{a}$	$0,0021 \pm 0,0016^{a}$	$0,0026 \pm 0,0017^{a}$
SH	2	$0,738 \pm 0,006^{b}$	$0,064 \pm 0,004^{b}$	$0,080 \pm 0,004^{b}$
	8	$0,652 \pm 0,003^{d}$	$0,153 \pm 0,001^{d,e}$	$0,190 \pm 0,007^{e}$
	24	$0,638 \pm 0,005^{e}$	$0,154 \pm 0,001^{d,e}$	$0,194 \pm 0,001^{e}$
	48	$0,623 \pm 0,002^{f}$	$0,174 \pm 0,002^{e,f}$	$0,218 \pm 0,001^{g}$
SM	2	$0,708 \pm 0,006^{c}$	$0,061 \pm 0,009^{b}$	$0,080 \pm 0,008^{b}$
	8	$0,638 \pm 0,014^{e,f}$	$0,123 \pm 0,011^{c}$	$0,162 \pm 0,013^{d}$
	24	$0,569 \pm 0,005^{g,h}$	$0,146 \pm 0,002^{d}$	$0,204 \pm 0,001^{f}$
	48	$0,554 \pm 0,006^{i}$	$0,175 \pm 0,003^{f}$	$0,241 \pm 0,001^{h}$
SS	2	$0,700 \pm 0,003^{c}$	$0,076 \pm 0,009^{b}$	$0,098 \pm 0,002^{c}$
	8	$0,617 \pm 0,015^{e,f}$	$0,141 \pm 0,001^{c,d}$	$0,186 \pm 0,016^{d}$
	24	$0,564 \pm 0,003^{h}$	$0,181 \pm 0,005^{f}$	$0,243 \pm 0,004^{h}$
	48	$0,565 \pm 0,016^{g}$	$0,187 \pm 0,011^{f}$	$0,247 \pm 0,005^{h}$

Letras diferentes en una misma columna indican diferencias significativas ($p < 0,05$).

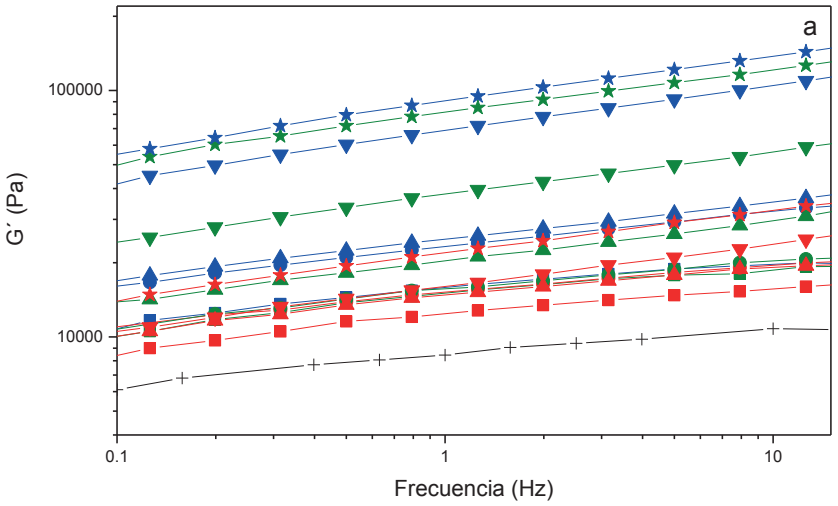
3.2 Ensayos oscilatorios

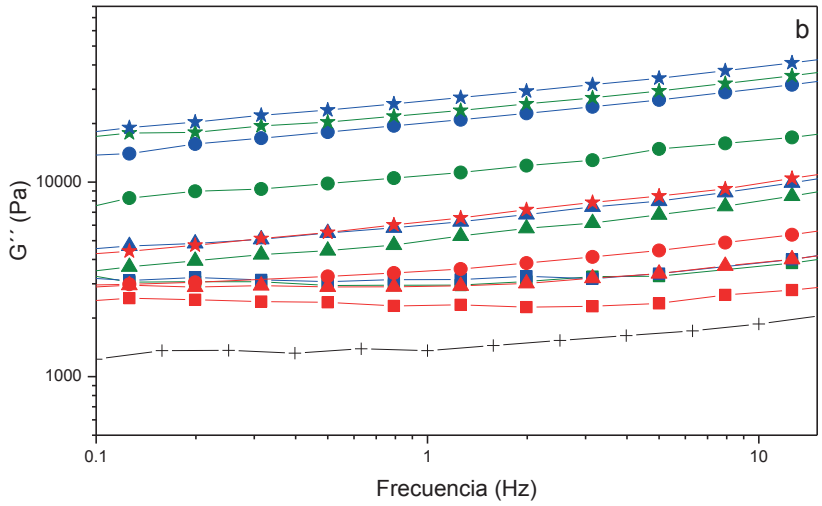
El módulo de almacenamiento o elástico (G'), el módulo de pérdida (G'') y la viscosidad compleja (η*) en función de la frecuencia angular para 0, 2, 8, 24 y 48 h de SH, SM y SS, se muestran en la **Figura 1**.

G' y G" presentaron una ligera dependencia con la frecuencia angular (**Fig. 1a y 1b**). La dependencia del módulo de almacenamiento fue directamente proporcional a la frecuencia. Un leve incremento en el módulo se correspondió con un aumento de la frecuencia. Con respecto a la dependencia del módulo de pérdida, a bajas frecuencias se observó un "*plateau*" en las muestras que presentaban menor contenido de sal. Para muestras con mayor tiempo de salado (> 8 h) el "*plateau*" seguramente se evidenció a frecuencias más bajas que las evaluadas en este ensayo, ya que G´´ mostró una pendiente con la frecuencia desde el comienzo. En todos los casos, G' excedió los valores G´´, indicando un comportamiento sólido predominante.

Analizando el efecto del tiempo sobre los métodos de salado, los tres procedimientos (SH, SM y SS) presentaron un aumento en el módulo elástico y de pérdida con el incremento del tiempo de salado asociados a la ganancia de sal y deshidratación. Un mayor contenido de sal provoca mayor agregación de proteínas y contracción de las fibras musculares [14]. Por otro lado, un mayor contenido de humedad ejerce mayor efecto plastificante, es decir, mayor aporte de flexibilidad por reducción de fuerzas intermoleculares y mayor movilidad de moléculas. Este último comportamiento se vio reflejado para el tejido de merluza fresca y para tiempos cortos de salado donde las muestras presentaban mayor contenido de agua (**Tabla 1**). Thorarinsdottir [15] reportó

resultados similares sobre los módulos durante el salado de bacalao por vía seca y húmeda.





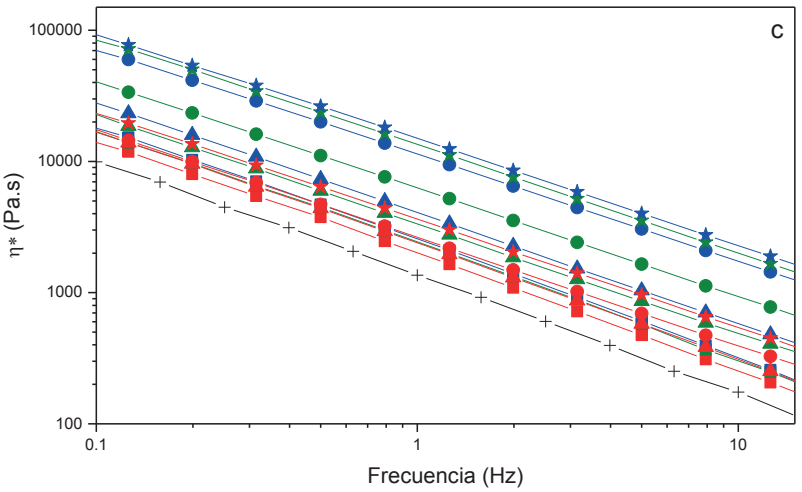


Fig. 1. Barrido de frecuencias para músculo de merluza fresco (+) y salado por 2 h (■), 8 h (▲), 24 h (●) y 48 h (★). a) Módulo de almacenamiento (G'), b) módulo de pérdida (G'') y c) viscosidad compleja (η*). SH (■), SM (■) y SS (■).

Analizando el efecto del método de salado, los valores de G' para SH con 48 h de salado fueron similares a los alcanzados con 8 h de SS y SM (**Fig. 1a**). Por otro lado, los métodos de salado seco y mixto, presentaron comportamientos similares, con valores levemente mayores en los espectros mecánicos para el SS durante las primeras 24 h; luego, estas diferencias se fueron reduciendo presentando una estructura similar a las 48 h de salado, acorde con los valores de z_{NaCl} determinados. Las diferencias encontradas entre métodos se deben a los cambios conformacionales sobre las proteínas miofibrilares y sobre los componentes estructurales como el colágeno del tejido conectivo [14]. Valores altos de G' (salado seco y mixto) se relacionaron con una mayor degradación y agregación de las miofibrillas y pérdida de colágeno; además de la mayor deshidratación que sufren las muestras procesadas por estos métodos.

Analizando el espectro de G´´ (**Fig. 1b**), se desprende prácticamente la misma tendencia que la encontrada para G´, incluso con diferencias aún más marcadas. Si se comparan los valores de G´´ para merluza fresca con los alcanzados al final del proceso de salado con los distintos métodos, se observa que el módulo de pérdida incrementó más de tres veces su magnitud con el método SH, mientras que para los métodos SS y SM el módulo superó cerca de 15 veces su magnitud original.

Independientemente del procedimiento aplicado, la viscosidad compleja (**Fig. 1c**) aumentó con el tiempo de salado. La presencia de NaCl en el músculo de merluza inicia la formación de una estructura tipo gel aumentando la viscosidad y favoreciendo la despolimerización de la miosina lo cual da lugar a un incremento en la hidrofobicidad de la superficie. Por ello, las muestras con mayor contenido de sal (48 h) presentaron valores de viscosidad significativamente más elevados. Por otro lado, la viscosidad

compleja disminuyó al aumentar la frecuencia angular presentando un comportamiento del tipo pseudoplástico.

Los resultados correspondientes a los espectros termo-mecánicos del músculo de merluza fresco y luego de 48 h de salado por distintos métodos (SH, SM y SS) se muestran en la **Figura 2**.

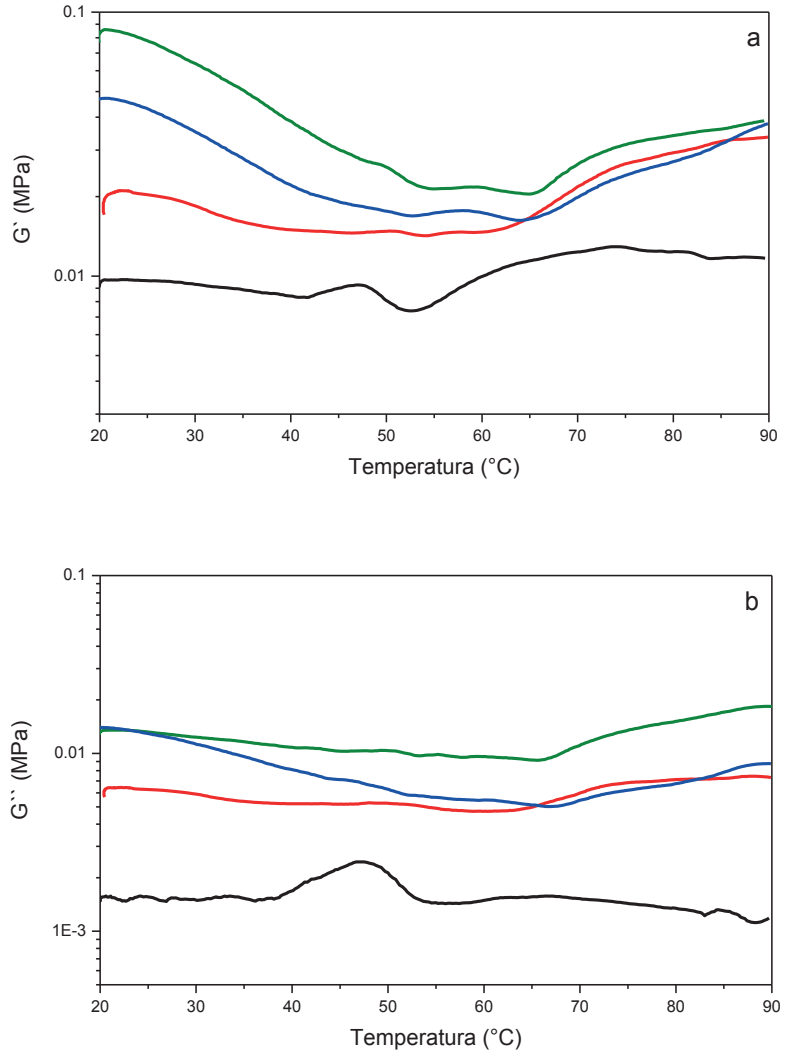


Fig. 2. Espectros mecánicos en función de la temperatura para músculo de merluza fresco y luego de 48 h de salado por distintos métodos. a) Módulo de almacenamiento (G') y b) módulo de pérdida (G''). Fresca (—) SH (—), SM (—) y SS (—).

Las curvas mostraron un comportamiento típico de gelación térmica de sistemas cárnicos, donde la mayor parte de los cambios están asociados a la desnaturalización de la miosina [16]. El módulo elástico de la merluza fresca disminuyó ligeramente desde los 20 °C hasta los 39 ± 4 °C (G´ = 0,0081 ± 0,0002 MPa). Pequeños descensos del valor de G´ entre 25 y 40 °C fueron asociados a disociación de la tropomiosina del esqueleto de F-actina y disociación de F-actina de su estructura de hélice [17]. El primer pico de G´ se obtuvo para 46,7 ± 0,4 °C (G´ = 0,010 ± 0,002 MPa), luego se observó un leve descenso de G' hasta los 53,6 ± 1,3°C (G´ = 0,0079 ± 0,0007 MPa). Varios estudios han reportado que las proteínas miofibrilares, especialmente miosina y actina, son responsables de la gelificación. La cadena pesada de miosina es la principal subunidad involucrada en dicho proceso; mientras que en lo que respecta a las cadenas ligeras, parece ser que su rol es dependiente de la fuerza iónica [18]. El desplegamiento de la miosina, causa un incremento en la fluidez de la estructura preformada del gel y puede interrumpir algunos entrecruzamientos que existen durante el estado inicial, resultando en el descenso del valor de G´ [18]. Howell et al. [19] reportaron una temperatura de desnaturalización para la miosina de 42 °C y 45,7 °C para bacalao (*Gadus morhua*) y trucha (*Salmo gairheri*), respectivamente. El segundo máximo se obtuvo para 74,1 ± 0,8 °C (G´ = 0,0131 ± 0,0003 MPa) y puede ser atribuido a la formación de una red permanente con los filamentos de miosina desnaturalizada; luego de esta temperatura el módulo se mantuvo prácticamente invariable hasta el final del calentamiento, donde la miosina y la actina se encontraban completamente desnaturalizadas. Se cree que la actina es más resistente al aumento del contenido de sal en el músculo [18].

Como se observa en la **Figura 2**, las muestras saladas (48 h) presentaron inicialmente un valor de G´ significativamente mayor en comparación con la merluza fresca. A medida que avanzó el calentamiento, se observó un descenso inicial de G´ más pronunciado en muestras saladas en comparación con la merluza fresca, siendo esta caída más abrupta para SS y SM y en menor medida para SH. El módulo de almacenamiento en muestras SH y SS descendió entre 20 y 46 °C; luego, se mantuvo hasta los 67 °C aproximadamente, superada dicha temperatura G´ creció hasta el final del calentamiento. En el caso de SM, G´ descendió desde el comienzo del calentamiento hasta aproximadamente 52 °C. Para los tres métodos, las muestras saladas presentaron un pico previo al ascenso final del módulo, pero desplazado a temperaturas mayores. A medida que la cantidad de agua libre disminuye, es necesaria una mayor temperatura para poder desarrollar la estructura tipo gel. Las diferencias encontradas entre métodos de salado estarían directamente relacionadas con el contenido de agua y sal. Los métodos SS y SM presentaron una mayor pérdida de agua y una temperatura de desnaturalización (Td) levemente mayor, mientras que las muestras procesadas con SH mostraron mayor contenido de humedad y una Td más cercana a la merluza fresca.

En general, se observó que la ganancia de sal disminuye la estabilidad térmica de las proteínas miofibrilares, siendo necesaria una mayor temperatura para poder desarrollar la estructura de gel. La miosina y la actina prácticamente convergieron a un mismo pico de Td ya que la temperatura del primer pico se vio incrementada. Estos resultados concuerdan con lo reportado por Zhou y Labuza [20], quienes encontraron menores valores de temperaturas de desnaturalización en tejidos con mayor actividad de agua y, por ende, con una mayor movilidad de las proteínas.

3.3 Microscopía SEM

La microfotografías de filetes de merluza frescos (0 h) y salados durante 0,5, 4, 8 y 48 h por distintos métodos (SH, SM y SS) se muestran en la **Figura 3**.

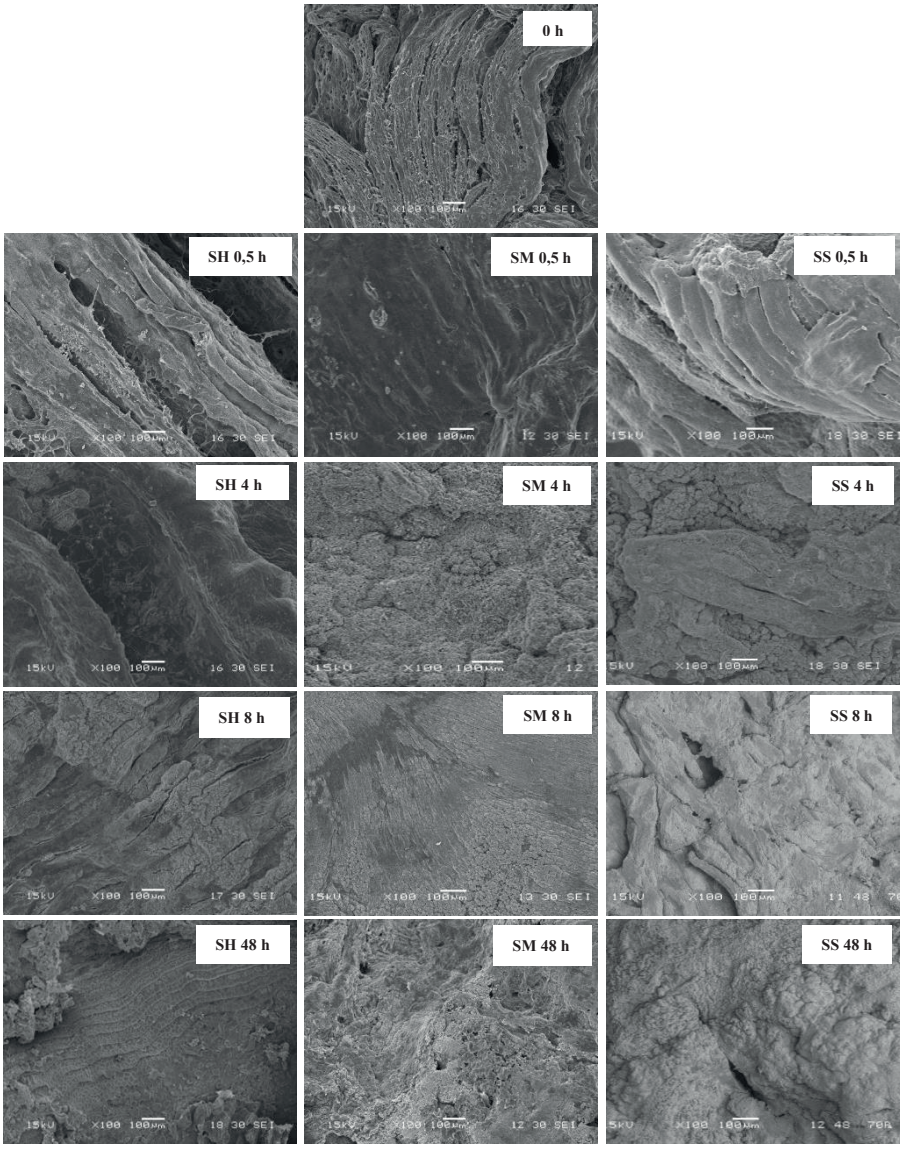


Fig. 3. Imágenes de microscopia electrónica de barrido para tejido de merluza fresca y salada por diferentes métodos (SH, SM y SS). Tiempos de salado: 0, 0,5, 4, 8 y 48 h.

El tejido muscular está constituido por fibras musculares, las cuales están rodeadas por tejido conjuntivo que las mantienen unidas. El tejido conjuntivo que rodea a las células musculares forma una capa delgada que constituye el endomisio; a su vez, un haz de fibras musculares con endomisio son rodeadas por una capa de mayor grosor de tejido conjuntivo que constituye el perimisio; varios haces de fibras musculares forman un músculo que es rodeado por una capa aún más gruesa que forma el epimisio. La unidad estructural y funcional del músculo estriado se llama sarcómero. El sarcómero contiene la matriz de filamentos de actina y miosina. Los filamentos gruesos de miosina están intercalados con los filamentos delgados de actina [3]. Es sabido que con el microscopio electrónico se puede observar mejor la estructura del sarcómero, con filamentos finos de actina, tropomiosina y troponina, y filamentos gruesos dispuestos de manera regular formados por miosina [3].

En relación a lo anterior, la microfotografía del tejido fresco de merluza mostró un paquete organizado de miofibrillas con presencia de tejido conectivo y pocos espacios intercelulares (0 h). Sin embargo, durante el salado, la microestructura del músculo se alteró significativamente (**Figura 3**).

Analizando el efecto del tiempo sobre los métodos de salado, para 0,5 h, las muestras SH mostraron una ligera contracción de las miofibrillas y aumento de los espacios intercelulares. Además, en las microfotografías, se observaron pequeños depósitos de sal en las fibras y desprendimiento del tejido conectivo (SH 0,5 h). Para las muestras SM y SS, se observó que sólo 0,5 h de salado fueron suficientes para que las fibras del tejido de merluza queden prácticamente cubiertas en su totalidad por una fina capa de sal. Efecto que se evidenció a las 4 h para SH. A medida que avanzó el tiempo de salado, se observó un aumento gradual en el espesor de la capa de sal que recubre las fibras, más notorio en las micrografías con salado SS. Para 48 h, en las micrografías SS y SM, se observó la formación de una costra gruesa irregular (ya evidente a las 8 h en el SS), lo que sugeriría mayor daño o desnaturalización proteica por estos métodos de salado (SS 48 h; SM 48 h) [21]. En contraste, para 48 h de salado húmedo, se evidenció un patrón hexagonal que formaron los cristales de sal de menor tamaño. Una vez saladas las fibras, por efecto de la desecación de la capa superficial, el tejido se contracta y se fractura y empiezan a desarrollarse los polígonos (SH 48 h). La salmuera sube por capilaridad por estas fisuras y se cristaliza al llegar a la superficie constituyendo los brotes de pequeños cristales de sal. Finalmente, el músculo queda cubierto de placas hexagonales y pequeños surcos de sal. Esta textura tan característica del salado húmedo, se evidencia naturalmente de forma macroscópica en algunos salares del mundo [22].

Durante los salados seco y mixto, los cristales de sal que cubren los filetes de pescado crean una mayor diferencia de concentración entre el exterior y el interior de los filetes, lo que provoca una mayor tasa de penetración de sal y deshidratación. El método de inmersión por salmuera, en cambio, controla más fácilmente la absorción de sal y reduce la agregación y desnaturalización de las proteínas [14]. En general, el salado fuerte de los filetes conduce a cambios irreversibles en las proteínas miofibrilares, especialmente en la molécula de miosina. Se cree que la agregación más fuerte de proteínas se produce en los filetes salados en seco [15].

La información sobre el análisis microestructural en el músculo de alimentos en relación con el salado es limitada. Sigurgisladottir et al. [23] comparó el efecto del salado

seco y húmedo en filetes de salmón. Encontraron que el contenido de sal fue similar para ambos métodos, sin embargo, el salado seco tendió a disminuir en mayor medida el área de la sección transversal de la fibra, debido a mayores gradientes de concentración y extracción de agua del músculo en comparación con los inmersos en salmuera. El análisis microestructural del músculo de cerdo salado en salmuera de NaCl al 3 %, 7 %, 10 % y 20 % mostró que bajas concentraciones de NaCl dieron como resultado la hinchazón de las fibras musculares y absorción de agua (efecto salting-in). Lo contrario se observó a concentraciones más altas (20 %), es decir, las proteínas se agregaron dando lugar a disminuciones en el volumen de las fibras y deshidratación del músculo (efecto salting-out) [24], [25].

4 Conclusiones

El estudio mostró que las variaciones en el contenido de agua y sal en el músculo de pescado, tienen un efecto significativo sobre los cambios conformacionales de las proteínas miofibrilares y sobre los componentes estructurales del músculo como el colágeno del tejido conectivo, dependientes, a su vez, del método de salado aplicado. Los principales cambios ocurrieron durante el salado seco, donde el contenido de sal (z_{NaCl}) en el músculo fue mayor en comparación con los métodos húmedo y mixto. En el SS se observaron los mayores incrementos de las propiedades reológicas (G´, G´´ y η*), temperatura de desnaturalización y mayor degradación de la estructura proteica. Los filetes inmersos en salmuera, en cambio, soportaron la menor desnaturalización a través del proceso de salado. Esta observación estuvo de acuerdo con las microfotografías SEM de los filetes. Inmersión en salmuera sería, por lo tanto, el método de salado recomendado en la producción de merluza salada, dando como resultado un producto con un menor daño superficial por salado. El estudio de las propiedades reológicas y el análisis de la microestructura, desempeñó un papel importante en la comprensión del comportamiento muscular durante el procesamiento.

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Evaluación de la Viabilidad de Cepas Probióticas de *Lactobacillus* Encapsuladas en Micropartículas de Pectina para uso en Matrices Vegetales

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Abstract. Las frutas representan un sustrato alternativo con gran potencial para el desarrollo de alimentos funcionales probióticos; sin embargo sus características intrínsecas como la acidez, representan un desafío para la supervivencia de las cepas. En el presente trabajo se propone la co-encapsulación de dos cepas probióticas (*Lactobacillus casei* ATCC 393 y *L. rhamnosus* ATCC 53103) en microgeles de pectina mediante gelación ionotrópica con inulina de distintos orígenes como estrategia para mejorar la viabilidad en condiciones de almacenamiento en refrigeración. Los resultados muestran que el diámetro promedio de las partículas encapsuladas no se vio afectado por los factores analizados, en tanto que la eficiencia de encapsulación fue > 90%. Los recuentos de ambas cepas al cabo de 6 semanas de ensayo fueron mayores a 7 unidades logarítmicas lo cual asegura una concentración de células viables acorde a las normativas vigentes para ser considerado un alimento funcional probiótico.

Keywords: *Lactobacillus,* Microencapsulación, Pectina, Inulina.

1 Introducción

La inclusión de cultivos probióticos en distintos alimentos se ha realizado tradicionalmente en productos de base láctea, sin embargo la creciente presencia de intolerancias, alergias y distintos regímenes alimentarios, promueven el uso de matrices alternativas no lácteas. En este contexto, las frutas y sus derivados representan sustratos interesantes para la elaboración de un alimento probiótico, ya que además de sus características nutritivas, son aceptadas por todos los grupos etarios y percibidas como alimentos saludables por sí mismos. Sin embargo el principal desafío en el desarrollo de alimentos funcionales a base de frutas es garantizar la supervivencia de las cepas

durante el almacenamiento debido principalmente a su naturaleza ácida. Entre las estrategias propuestas para proteger a los probióticos hasta su llegada al sitio de acción, manteniendo y/o aumentando su viabilidad y actividad están: la fortificación con prebióticos, dando lugar a un alimento simbiótico, y la microencapsulación, utilizando matrices que actúen como una barrera física biocompatible protegiendo a las células bacterianas del ambiente externo [1,2].

La inulina es un carbohidrato de reserva de las plantas, posee propiedades prebióticas y es considerada GRAS. A nivel industrial se la obtiene mayormente de la achicoria; sin embargo un cultivo de creciente interés para su obtención es el topinambur (*Helianthus tuberosus* L.) debido a su interesante y poco explorado potencial agronómico en Argentina y otras partes del mundo [3]. La pectina, de amplio uso en la industria de alimentos, representa un ingrediente de alto valor funcional que ha ganado atención como agente encapsulante de probióticos debido a su bajo costo, no toxicidad y biocompatibilidad, además de ser resistente a las enzimas gastrointestinales y es fácilmente digerida por las pectinasas generadas por la microbiota colónica [4].

El objetivo del presente trabajo consistió en evaluar la microencapsulación en microgeles de pectina con el agregado de inulina de distintos orígenes como estrategia para mejorar la viabilidad de dos cepas probióticas en condiciones de almacenamiento en refrigeración.

2 Materiales y Métodos

2.1 Materiales

Como prebióticos de interés, se utilizaron inulina comercial (IC) de grado alimentario (Sigma-Aldrich Chemical Co.) e inulina obtenida de *Helianthus tuberosus* (ITub), donada por la Dra. Irene Rubel (Universidad Nacional del Centro de la Provincia de Buenos Aires). La metodología de extracción y caracterización química de ITub se informan en Rubel [5] y Rubel [3].

En la formulación de los microgeles se utilizó pectina de bajo metoxilo Genu Pectin LM104 AS (CPKelco, Limeira, Brasil), con un grado de esterificación del 27% y el 20% de los grupos carboxilos reemplazados por grupos amida (datos del fabricante). Como fase dispersante se utilizó aceite de girasol Molinos Rio de la Plata S.A. (Buenos Aires, Argentina) y como agente entrecruzante se utilizó cloruro de calcio (Anerda S.A., San Fernando, Buenos Aires, Argentina).

2.2 Microorganismos y condiciones de cultivo

Se utilizaron dos cepas de reconocida capacidad probiótica, *Lactobacillus casei* ATCC 393 y *Lactobacillus rhamnosus* ATCC 53103 (ATCC, Rockville, MD). Para los ensayos, un vial de cada cepa fue re-suspendido en caldo Man, Rogosa y Sharpe (MRS, Biokar Diagnostics, Beauvais, France), y cultivado durante 24 h a 37 ± 1ºC. Cada cultivo fue centrifugado a 5000 x g durante 10 min y el pellet lavado dos veces con solución buffer fosfato (PBS). Para la preparación de los inóculos cada cepa fue re-suspendida en soluciones de PBS+prebiótico (IC e ITub) hasta alcanzar una carga

microbiana de ~ 10 log UFC/mL. Las concentraciones bacterianas finales se determinaron por recuento en placa en agar MRS (48h a 37ºC). Se utilizaron soluciones de inulina al 1% (p/v) previamente esterilizadas por microfiltración con membranas de 0,22 µm de tamaño de poro (Gamafil S.A., Argentina).

2.3 Preparación de las micropartículas

Para la encapsulación de cada combinación probiótico-prebiótico se utilizó el método de gelación ionotrópica mediante la formación de una emulsión agua/aceite utilizando pectina de bajo metoxilo al 2% (p/p) y una solución de $CaCl_2$ al 1% de acuerdo a lo establecido por Holkem [6] con algunas modificaciones. Brevemente, se preparó una solución de pectina en agua destilada estéril bajo agitación magnética (300 rpm, 2 h) a 50ºC, se dejó enfriar hasta alcanzar una temperatura de 30ºC momento en el cual se incorporó la solución de probióticos y se agitó durante otros 30 min. Para la preparación de la emulsión agua/aceite se mezclaron 20 mL de dicha mezcla con 20 mL de aceite de girasol comercial que contenía Tween 80 (Merck KGaA, Alemania) al 1% (v/v), y se utilizó un sistema de agitación mecánico de paletas planas a 1000 rpm por 4 min. Las micropartículas se obtuvieron mediante goteo de una emulsión de $CaCl_2$ de similares características sobre la emulsión agua/aceite original, que contenía los probióticos al mismo tiempo que se mezcló con el sistema de agitación mecánica para lograr la formación de las microesferas de gel. Luego de un paso previo de maduración bajo agitación suave (< 300rpm) durante 1 h aproximadamente las microesferas fueron lavadas con solución al 0,1% de Tween 80.

Se calculó el diámetro promedio en base área (D_{32}) siguiendo la siguiente fórmula

$$D_{32} = \sum_{i=0}^{n} d_i^3 \Big/ \sum_{i=0}^{n} d_i^2$$

Donde d_i es el diámetro de cada partícula y n es el total de partículas. Para esto se analizaron micrografías digitales tomadas con un microscopio Primo Star-Zeiss de las emulsiones resultantes y se analizaron con el software Image J 1.50i [National Institute of Health (NIH), Bethesda, MD, USA].

Eficiencia de encapsulación (EE)

La EE se determinó mediante como se indica en Reid [7]:

$$EE = (Log\ 10\ N / Log\ 10\ N_0) \times 100$$

Donde N es el número de células viables encapsuladas y liberadas de las micropartículas y N_0 el número de células libres (suspensiones iniciales) agregadas inmediatamente antes de la encapsulación.

Para su determinación, 0,1 g de micropartículas se suspendieron en citrato de sodio 0,1 % (p/v, pH 6,2) y luego de 20 min bajo agitación suave para lograr la disolución se realizaron diluciones decimales y se procedió al recuento celular en agar MRS a 37ºC durante 48h.

Supervivencia de las células probióticas microencapsuladas bajo condiciones de almacenamiento.

Las cepas co-encapsuladas con los prebióticos fueron almacenadas a temperatura de refrigeración (4ºC) por 6 semanas. Para determinar la supervivencia de las mismas se tomaron muestras semanalmente y se realizaron recuentos en placa en agar MRS a 37ºC por 48 h, siguiendo la metodología detallada en el apartado anterior.

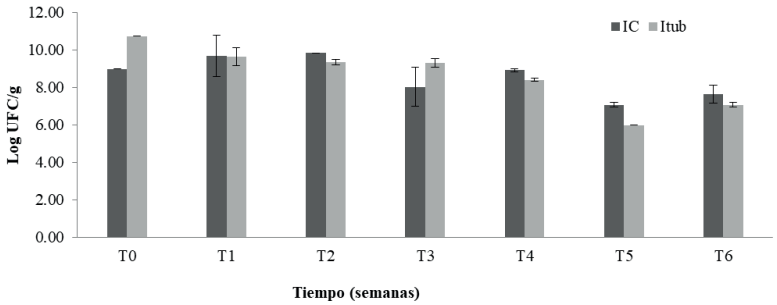
3 Resultados y Discusión

Las reglamentaciones nacionales e internacionales establecen que para que un alimento sea considerado probiótico al momento de su consumo debe presentar una carga de células probióticas viables entre 10^6 y 10^9 UFC/g o mL, por lo tanto mantener su viabilidad es imprescindible. Es por esto que en el presente trabajo se planteó el uso combinado de técnicas de microencapsulación con el agregado de prebióticos como estrategia para la asegurar la viabilidad en condiciones de almacenamiento.

La EE en las condiciones ensayadas fue del 94 ± 9 % para ambas cepas, siendo el diámetro promedio (en base área) de las partículas resultantes de entre 60 y 80 µm para IC y de 90 µm en el caso de ITub, sin encontrarse un efecto significativo entre los factores analizados (la cepa probiótica y el tipo de inulina). En cuanto a la supervivencia al cabo de las 6 semanas a 4ºC, *L. casei* presentó recuentos de 7,65 ± 0,49 log UFC/g (IC) y 7,09 ± 0,12 log UFC/g (ITub) mientras que *L. rhamnosus* presentó recuentos de 9,74 ± 0,06 log UFC/g (IC) y 8,65 ± 0,49 log UFC/g (ITub). En las Figuras 1 A y B se puede observar la progresión de ambas cepas a lo largo del tiempo. Como se puede observar tanto IC como Itub presentan un gran potencial simbiótico, manteniéndose niveles de células viables por encima de las recomendadas por las legislaciones. En el caso de ITub se presenta como alternativa no convencional para un aprovechamiento integral de recursos poco explorados como es el caso de los tubérculos de topinambur (*H. tuberosus* L.).

La inmovilización en microgeles de pectina con el agregado de prebiótico brindó un buen soporte de protección bajo condiciones de almacenamiento a temperaturas de refrigeración, siendo el efecto del tipo de prebiótico cepa dependiente. Los resultados muestran un promisorio futuro hacía la administración de los mismos suplementos funcionales en productos a base de frutas asegurando una carga microbiana adecuada en el sitio de acción en el huésped.

A



B

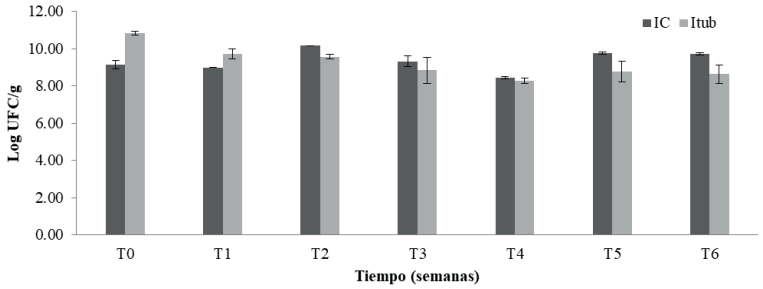


Fig. 1. Supervivencia de *L. casei* (A) y *L. rhamnosus* (B) co-encapsuladas con Inulina Comercial (IC) e Inulina obtenida de *H. tuberosus* (ITub) a lo largo de 6 semanas a 4ºC.

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Modelling Planetary Ball Milling of Rice Starch

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Abstract. Rice starch was physically modified by thermo-mechanical action avoiding the use of chemical agents and minimizing the process waste. The aim was to evaluate the aptitude of Rittinger and Holmes equations to simulate the relationship between milling energy and particle size. First, the particle size distribution was fitted by the Rosin-Rammler-Bennett (RRB) equation determining the effect of milling energy on model parameters n and D_{65}. Particle size distribution was measured by laser diffraction and the specific milling energy provided by the planetary ball mill (PM100, Retsch, Germany) was determined as a function of milling conditions (10-40 min, 400 rpm). Due to the asymmetric profile of particle distribution at all levels of milling energy (0.26 - 4.08 kJ/g), the fit by the RRB model resulted very satisfactory ($R^2 > 0.98$). As milling energy changed from 0.26 to 1.99 kJ/g, the homogeneity index increased (n: 0.86-1.86) and the values of D_{65} decreased from 85 to 15 μm. Between 1.99 and 4.08 kJ/g, the model parameters showed an asymptotic tendency. Polynomial relationships between these model parameters and milling energy were found ($R^2 > 0.91$). The prediction of energy-size relationship by Holmes equation was more satisfactory ($R^2 = 0.98$) than that of the Rittinger model ($R^2 = 0.75$). This revealed the significant effect of heat dissipation on the milling process. The results pointed out the relevance of the mechanic activation in high impact milling and corroborated the ability of Holmes equation to simulate the ultra-fine pulverization, which takes place in the planetary ball mill.

Keywords: Ball Milling, Specific Milling Energy, Particle Size.

1 Introduction

Starch is obtained from different sources such as cereal grains or tubers and it has important applications in the food and non-food industries [1]. In particular, rice starch is a popular ingredient in infant food products where is used to create soft gel structures. It is also valued due to its excellent shelf-life stability and its ability to act as a fat replacer [2].

Native starch is frequently modified by chemical, physical or biotechnological procedures in order to improve its functional properties [1]. Among these methods, physical treatments such as extrusion [3], ball milling [4], jet-milling [5], and hydrothermal [6] or high pressure treatments [7] are becoming popular because they are considered good and environmentally friendly techniques.

Recently, the high-impact dry milling has promoted the interest of researchers as a tool for the physical modification of starches [8, 9, 10, 11]. This type of milling can cause significant changes in the morphology and crystalline structure of starch granules, which affects their physicochemical and functional properties, and thus expands their industrial applications [12, 13].

Traditional milling models are based on relationships between particle size and specific milling energy [14]. The size reduction is a process with a high level of energy consumption and low efficiency. Since the particle surface increases as the particle size is reduced, the measure of the process efficiency is based on the energy required to create a new surface [15]. There are three basic postulates for the prediction of energy requirements for the particle comminution: the laws of Rittinger [16], Kick [17], and Bond [18]. Later, Holmes [19] proposed a generalised milling equation. Particularly, Rittinger equation has been successfully applied to model ultra-fine grinding [14].

Milling energy is dependent on milling conditions, which are frequently expressed in terms of grinding time and rotation speed, and these variables are strongly dependent on the mill device [20, 21]. The application of milling models is important to control the process and to design milling protocols to produce a specific starch modification.

Several methods for particle size measurement have been reported based on sieving methods, microscope counting techniques, sedimentation, and particle flow scanning, such as laser diffraction [22]. Particle size distribution can be described by mathematical expressions in terms of relative frequencies or cumulative frequencies [14]. The Gaussian model is useful to represent the symmetric particle distribution obtained through chemical condensation or precipitation processes. However, to evaluate the particle distributions obtained by crushing and grinding operations, the Rosin–Rammler–Bennet (RRB) model is frequently used, which describes the particle distribution of food powders that do not present a symmetric distribution [14, 22, 23].

Simulation studies of the grinding process in food area are still very scarce which are based on the relationships between milling energy and particle size reduction. For this reason, the objective of the present work was to evaluate the aptitude of the Rit- tinger and Holmes equations to simulate the energy-size relationship during rice starch pulverization. For this purpose, the specific milling energy was recorded as a function of milling time, and the particle size analysis was first performed.

2 Materials and Methods

2.1 Material

Native rice starch of food grade (Remy B7, Beneo GmbH, Germany) was supplied by Saporiti S.A. (Buenos Aires, Argentina). The amylose content of the rice starch (18.4 g/100 g of total starch) was obtained according to an iodine binding-based method [24].

Chemical composition (dry basis) of rice starch was provided by the manufacturer as follows: 88.7 % carbohydrates (by difference), 13.7 % moisture, 1.0 % protein, 0.0 % lipid, 0.2 % ash.

2.2 Rice Starch Modification by Ball Milling

Starch was grinding in a planetary ball mill model PM 100 manufactured by Retsch (Retsch GmbH, Germany) with zirconium jar (500 mL) and balls (diameter: 5 mm) at different levels of milling energy within 0.26 - 4.08 kJ/g and constant rotational speed of 400 rpm. A previous calibration was performed by using an empty jar (energy at "ralenti") to obtain milling energy [25]. Specific milling energy was expressed in kJ/g of starch. Starch sample (115 g) and five times weight balls were used according to the milling protocol proposed by Gonzalez et al. (2018) [26] which involved pauses of 40 min each 10 min of grinding and a change in the rotational direction of the jar every 30 s. By this method, sample temperature was controlled and it never exceeded 55 °C. Native rice starch was adopted as the control sample.

2.3 Determination of Particle Size Distribution

Particle size distribution was determined by static light scattering (SLS) in a Mastersizer 2000 device (Malvern Instruments Ltd., Worcestershire, UK), which is equipped with a dispersion unit Hydro 2000MU. The pump was operated at 1800 rpm. Bi-distilled water was used as the dispersing agent, whose diffraction index and absorptivity were 1.53 and 0.001, respectively. The instrument provides the volume size distribution. Characteristic parameters: D_{50} (median) and D_{80} (corresponding to the diameters of 50 % and 80 % of cumulative volume, respectively), specific surface area (SSA), mean volumetric diameter ($D_{4.3}$), and dispersion index (Span) were obtained from the device software (Malvern Application v5.60, Malvern Instruments Ltd., Worcestershire, UK). The average of five replicates was reported.

2.4 Particle Size Distribution Model

Particle size distributions of starch samples obtained with different milling energy levels were adjusted by the Rosin-Rammler-Bennett (RRB) model (Equation 1), which is commonly used for the characterisation of food powders when they do not follow a normal distribution [22].

$$F(x) = 1 - \exp\left[-\left(\frac{x}{D_{63}}\right)^{n}\right] \quad (1)$$

Where, F(x) is the accumulated distribution, x the particle size, D_{63} the particle diameter correspondent to 63.2 % of the accumulated distribution, and n a constant associated with the homogeneity of the sample. Low n values are associated with high size dispersion, while high values of this parameter involve greater uniformity. Yan and Barbosa-Cánovas (1997) [27] evaluated different distribution models for various food

matrices and concluded that such models present enough flexibility to describe the distribution of powders, and they pointed out that RRB equation is one of the most appropriate equations for its characterisation.

2.5 Energy-Particle Size Milling Models

Rittinger Model. Rittinger (1867) [16] proposed that the energy required for the reduction of the particle size is directly proportional to the increase of the created surface. If the energy required for particle fragmentation is expressed based on the particle diameters, the resulting equation is as follows:

$$E = C_r \left(\frac{1}{x_2} - \frac{1}{x_1}\right) \quad (2)$$

Where, E is the specific milling energy by mass unit (kJ/g), C_r the Rittinger milling coefficient, x_1 the initial particle size, and x_2 the particle size after milling. Diameter D_{63} in equation (1) was adopted as a measure of x.

Generalised Milling Model. Holmes (1957)[19] proposed equation (3), known as generalised milling model, which states that the energy required to produce a small change in the size of unit mass can be expressed as a power function of the size of the material.

$$\frac{dE}{dx} = -C\frac{1}{x^{n_1}} \quad (3)$$

The integrated form of the equation yields:

$$E = \left(\frac{c}{1-n_1}\right)\left(D_{xi}^{1-n_1} - D_{xf}^{1-n_1}\right) \quad (4)$$

Where n_1 and C are the parameters of the model, D_{xi} and D_{xf} are the diameter of the native rice starch and the diameter of the modified starch at a specific milling energy, respectively. Diameter D_{63} in equation (1) was adopted as a measure of D.

2.6 Statistical Analysis

Analysis of variance (ANOVA) and regression analyses were performed using the statistical program Statgraphics Centurion version XVI (Statistical graphics Corporation, USA), comparing the means by the least significant difference test of Fisher (LSD), with a confidence level of 95 %.

3 Results and Discussion

3.1 Particle Size Distribution

The effect of milling energy on particle size distribution can be seen in Fig. 1 for samples of native rice starch and modified starches in the planetary ball mill. The Figure shows the asymmetry of the curves. As the energy level increased, the curves moved towards the smaller size region and displayed a lower dispersion. Native starch (control) presented a bimodal distribution, with maximums at 28.2 μm and 148.3 μm, and the latter is more important as to volumetric fraction than the former. In contrast, starches modified by high impact milling showed monomodal distributions.

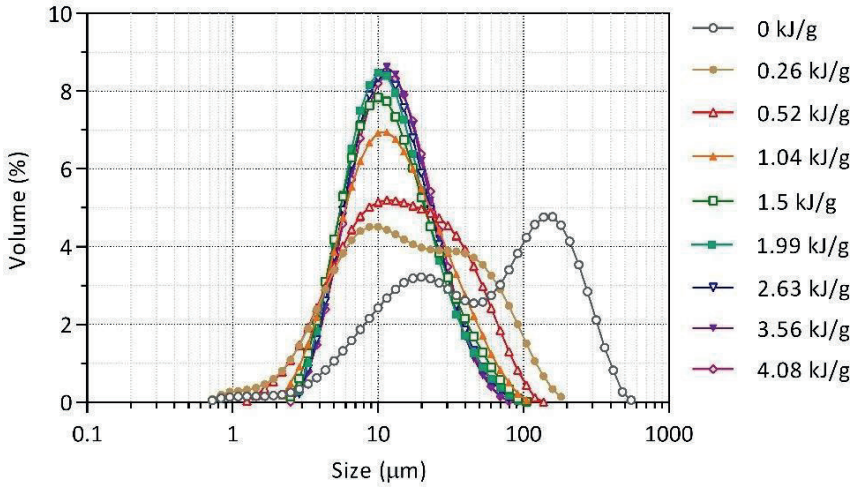

Fig. 1. Volume size distribution by static light scattering (SLS) of native rice starch (control, 0 kJ/g) and starches modified by ball milling at different energy levels.

It should be noted that starches milled at 0.26 kJ/g and 0.52 kJ/g presented a monomodal distribution (modes at 10.7 μm and 12.3 μm, respectively), but with a "shoulder" to the right of the maximum, showing larger particle remnants. In contrast, starches subjected to milling energies higher than 1.04 kJ/g presented a monomodal distribution (modes between 10.7 μm and 12.3 μm) with a defined "peak". Table 1 shows, as a function of milling energy, some characteristic parameters of the size distribution such as the values of D_{50} and D_{80} as well as the dispersion index (Span).

Between 0 and 1.99 kJ/g the values of D_{50} decrease from 60.9 to 12.2 μm but in the range 1.99 -4.08 kJ/g an slight increase in the values of median up to 13.2 μm was observed due to particle agglomeration. A similar effect of milling energy on $D_{4,3}$ and for D_{80} can be appreciated in the Table. Other authors [10, 28, 29] have reported two effects during ball milling: particle size reduction (grinding) and mechanical activation

of starch (agglomeration). They are dynamic equilibrium processes which were also detected by Tian et al., (2011) [29] in planetary ball milling of maize starch working at 500 rpm during 3 h. Powder activation by high impact grinding takes place when particles become smaller than the size of tough–brittle transition [4, 28]. As regards the dispersion index, it decreased as milling progressed, indicating an increase in starch homogeneity.

Table 1. Characteristic parameters of the particle size distribution of rice starches as a function of milling energy.

Energy (kJ/g) [Time] (min)	D_{50} Median [$D_{4,3}$] (μm)	D80 (μm)	SSA (m2/g)	Span (dimension-less)
0 [0]	60.9 ± 10.8^{a} [97.4 ± 10.0^{a}]	174.1 ± 16.5a	0.285 ± 0.031^{g}	3.9 ± 0.3^{a}
0.26 [5.4]	16.9 ± 0.6^{b} [29.3 ± 1.1^{b}]	48.5 ± 2.2b	0.622 ± 0.009^{a}	4.0 ± 0.0^{a}
0.52 [10.6]	15.5 ± 0.4^{b} [$22.9 \pm 0.8^{b,c}$]	36.5 ± 1.5c	0.579 ± 0.009^{b}	3.1 ± 0.1^{b}
1.04 [21.8]	13.4 ± 0.2^{b} [18.5 ± 0.6^{c}]	27.2 ± 1.1c,d	$0.559 \pm 0.004^{c,d,e}$	2.5 ± 0.1^{c}
1.5 [31.7]	12.4 ± 0.1^{b} [16.9 ± 0.5^{c}]	23.8 ± 0.9d	$0.570 \pm 0.003^{b,c}$	2.3 ± 0.1^{c}
1.99 [42.0]	12.2 ± 0.1^{b} [15.9 ± 0.3^{c}]	21.9 ± 0.6d	$0.567 \pm 0.004^{b,c,d}$	2.0 ± 0.1^{d}
2.63 [57.4]	12.8 ± 0.2^{b} [16.3 ± 0.5^{c}]	22.8 ± 0.9d	$0.547 \pm 0.006^{d,e,f}$	2.0 ± 0.1^{d}
3.56 [75.3]	12.9 ± 0.3^{b} [16.0 ± 0.4^{c}]	22.4 ± 0.8d	$0.541 \pm 0.006^{e,f}$	1.8 ± 0.0^{d}
4.08 [86.9]	13.2 ± 0.3^{b} [16.3 ± 0.6^{c}]	23.1 ± 1.0d	0.533 ± 0.007^{f}	1.9 ± 0.1^{d}

D_{50} and D_{80} represent the particle diameters that cumulative volume of particles are 50% and 80%, respectively. SSA: Specific Surface Area. Size dispersion index [Span = $(D_{90}-D_{10})/D_{50}$]. The reported values represent the average of five determinations ± the standard deviation. Values followed by the same online letter within a column do not differ significantly ($p < 0.05$).

3.2 Rosin-Rammler-Bennett Model

The particle size distributions of native and modified rice starches (Fig. 1) were adjusted by equation (1), and the values of the model parameters were determined by regression analysis: D_{63} (particle diameter corresponding to 63.2% of the accumulated distribution) and n; the latter is related to the homogeneity of sizes in the sample. Table 2 shows the values of the parameters of equation (1) for each level of milling energy.

Table 2. Parameters n and D_{63} of the Rosin-Rammler-Bennet equation, as a function of milling energy.

Energy (kJ/g)	n	D_{63} (μm)	R^2
0	0.86	85.07	0.994
0.26	1.02	23.97	0.992
0.52	1.22	20.06	0.993
1.04	1.51	16.31	0.991
1.5	1.65	14.76	0.989
1.99	1.80	14.10	0.990
2.63	1.81	14.66	0.991
3.56	1.88	14.61	0.992
4.08	1.86	14.99	0.993

As the energy increased, D_{63} values decreased from 85.07 to 14.1 μm, while n increased as the homogeneous character of the sample was accentuated. The degree of milling was similar to the one reported in the literature for other starches processed by ball milling [10, 30]. However, smaller particle sizes (2.9 -6.7 μm) can be obtained by jet-milling treatment where higher levels of rotational speed (1800-3900 rpm) are applied.

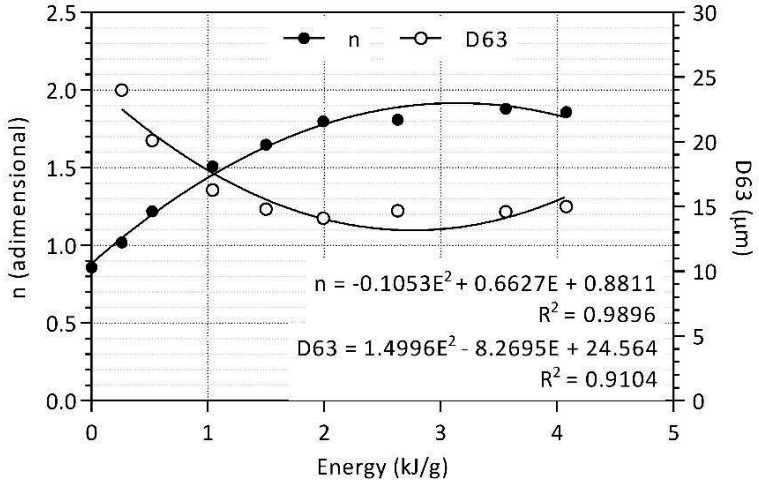

Fig. 2. Relationships between the parameters of the RRB equation and the specific milling energy.

Figure 2 shows the relationships of D_{65} and n with milling energy. Both parameters were successfully adjusted using second degree polynomials as a function of energy. It

can be seen that for energies higher than 1.99 kJ/g, both n and D_{63} tended to asymptotic values.

3.3 Holmes and Rittinger Milling Models

Table 3 shows the results of the regression analysis for the Holmes model (equation 3) using different characteristic sizes: D_{50}, D_{63} and D_{80}. Satisfactory adjustments ($R^2 > 0.92$) were obtained for the three cumulative diameters evaluated. The best adjustment was obtained for D_{63} ($R^2 = 0.98$) and, in this case, parameters C and n_1 adopted values of 34.08 kJ/[mg*$\mu m^{(1-n1)}$] and 4.2, respectively. For the three accumulated diameters evaluated, the values of n_1 were higher than 2, which, considering Rittinger model, confirms the obtaining of fine particles by planetary ball milling.

Table 3. Parameters and adjustment of the generalised equation (Equation 4) for accumulated diameters D_{50}, D_{63} and D_{80}.

Parameters:	D_{50}	D_{63}	D_{80}
C kJ/[mg*$\mu m^{(1-n1)}$]	940.9	29.8	1.4
n_1 (dimensionless)	5.6	4.2	3.0
R^2	0.9635	0.9833	0.9253

It should be clarified that the values of constants C and n_1 shown in Table 3 were obtained by taking only the energy values between 0 kJ/g and 1.99 kJ/g for regression since at higher energies no significant changes were noticed in the particle size decrease and the model did not provide an effective adjustment of the asymptotic part of the curve.

Figure 3 shows the relationship between energy and size. The exponential growth of the energy requirement is evident for particle sizes smaller than 20 μm as well as the loss of energy efficiency as milling progresses. The more the particle size is reduced, there are fewer weak areas available for rupture and, consequently, the fracture strength to be exceeded increases. When there are no more weak zones left, new cracks must be created to reduce the particle size, which requires additional energy. In this way, the energy requirement increases as the particle size decreases [4, 31].

The experimental values and those predicted by the generalised model (Equation 4) and the Rittinger model (Equation 2) are shown in Fig. 3. There are two aspects that can be highlighted: the evolution of the particle size reduction process (D_{63}) as a function of milling energy (0 – 1.99 kJ/g), and the good concordance between the experimental values and those predicted by Holmes model ($R^2 = 0.9846$).

In contrast, when using the Rittinger equation, the value of the C_R parameter was 0.024 kJ/[mg*μm^{-1}] and a less satisfactory result was obtained ($R^2 = 0.7499$). As Rittinger maintains that the energy consumed is proportional to the newly created surface, the lack of adjustment indicates that a significant part of the energy provided by the mill is dissipated as heat and it is not used for the reduction of the particle size [4, 14, 20, 22].

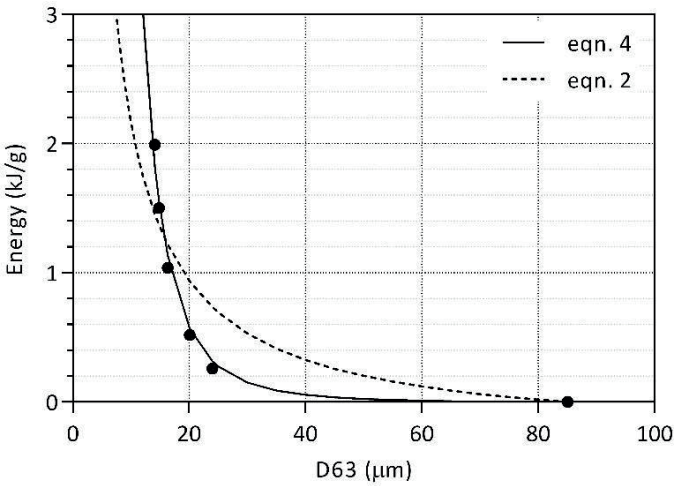

Fig. 3. Relationship between milling energy and particle diameter D63. (•): experimental data, (—): predicted values by the generalised Holmes equation, (- -): predicted values by the Rittinger model.

Furthermore, the Holmes n index should be considered, which connects the energy applied for the size reduction with the efficiency for the creation of new surface. Where n is 2, the Holmes equation is in agreement with the Rittinger model, and maximum efficiency is achieved. Therefore, the higher n value (4.2) obtained also points out that, in this case, the process takes place with less efficiency and there is a loss of energy. In this regard, Roa et al. (2014) [21], who obtained a value of n1 higher than two (2.71) by means of the generalised milling equation to simulate amaranth milling, have remarked the importance of the heat dissipation phenomenon when using a high impact mill.

4 Conclusions

The planetary ball milling was an efficient method to physically modify rice starch that avoids the use of chemical substances and the generation of waste during and after treatment. The milling energy had a significant effect on the particle size distribution that was determined by laser diffraction. The modified starches were found to have a smaller particle size and a greater homogeneity in size distribution, compared to native starch. A size reduction was observed between 0 and 1.99 kJ/g, while a slight size increase was observed for higher energies (1.99 – 4.08 kJ/g).
The size distribution curves were asymmetric and they could be satisfactorily modelled by means of the Rosin-Rammler-Bennett equation, whose parameters provided information about the size (D_{63}) and the sample homogeneity. D_{63} value was adopted as the

sample size when applying the Rittinger and Holmes models to simulate the energy-size relationship during milling.
While the Holmes equation provided a good adjustment of the experimental data, the Rittinger model was not satisfactory. From the analysis carried out based on the milling models, it could be inferred that not all the energy provided by the mill is used for size reduction. A significant part is dissipated as heat. This corroborates the importance of the heat dissipation phenomenon in high impact milling. The model presented is expected to be effective for controlling the degree of modification of rice starch, which is subject to the thermo-mechanical action typical of this type of milling. This allows the design of processes to obtain starches with specific structural and functional properties.

Acknowledgements

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Influence of olive mill waste polyphenols levels on carotenoid production by *Rhodotorula mucilaginosa*

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Abstract. Olive oil extraction performed with the two-phase extraction system generates a waste named "alperujo" or two-phase olive mill waste (TPOMW), which has a high percentage of water (65%), slightly acidic pH, high concentration of salts, organic matter and phenolic compounds. Because of these components, the alperujo is a significant source of environmental pollution, hindering the disposal of this waste. Nevertheless, biophenols have high nutraceutical and antioxidant power and could be used in the food, pharmaceutical and cosmetic industries. This work aimed to evaluate the ability of an aqueous extract from alperujo (AE) and the liquid fraction of alperujo (Alperujo water, AW), with different levels of phenols to sustain the growth and carotene production of *Rhodotorula mucilaginosa*. Extraction with ethyl acetate reduces the concentration of phenols from AE and AW, without affecting protein or glucose levels. The yeast was able to grow and produce carotenoids in all mediums, although growth was better when phenols were partially removed. Carotenoid production was significantly higher in the most concentrated dephenolized alperujo mediums (AE 30%, AW). Our study represents a new approach to the valorization of alperujo, with a dual benefit, the recovery of valuable compounds, i. e. biophenols and the bioproduction of new ones, i.e. carotenoids.

Keywords: Alperujo, Carotenoids, Waste Valorization, Microbial Growth,

1 Introduction

Olive oil extraction can be performed by the continuous two- or three-phase processes, in which the oil is obtained using centrifugal decanters. In the two-phase process, no water is added and a semi-solid waste composed of olive pomace and vegetation water is generated, called "alperujo" or two-phase olive mill waste (TPOMW) [1]. The alperujo is characterized by a pH of 4–6, low activity water [2] and almost 90% of its dry weight is organic matter comprising: lignin, cellulose, hemicellulose, lipids, carbohydrates and biophenols [3]. Olives contain a wide variety of phenolic compounds, such as: phenolic alcohols, (Hydroxytyrosol), secoiridoids (oleuropein and verbascosids) and flavonoids [4,5] with interesting biological activities [6]. However, they are considered responsible for alperujo phytotoxicity [7], since they affect seed germination, soil microbial ecosystem, and surfaces water [3, 7-8]. Therefore, removal of biophenols

from alperujo would have a dual impact on alperujo valorization, the recovery of a high-added-value product and a reduction in the toxicity of alperujo making it more suitable for subsequent bioprocesses. The objective of the present work is to studied the changes in the growth and production of carotenoids by the yeast *Rhodotorula mucilaginosa* when growing in mediums derived from alperujo before and after dephenolization.

2 Results and Discussion

2.1 Substrate characterization: dephenolized and non-dephenolized medium.

To reduce the polyphenol content present in alperujo we performed a liquid-liquid partition with ethyl acetate as in [5], a treatment that was shown to allow the recovery of these valuable compounds from alperujo. Since polyphenols have antibacterial activity, their removal could leave the AE and AW more suitable for bioprocess. As shown in Figure 1a, dephenolization with ethyl acetate effectively reduced polyphenol content in ~45 % in both AEs and about 30 % in AW. A reduction in pH was also observed in all mediums probably due to some hydrolysis of the ethyl acetate and the release of acetic acid that is water-soluble. Glucose and protein content were not affected by polyphenol extraction (Fig 1 c-d).

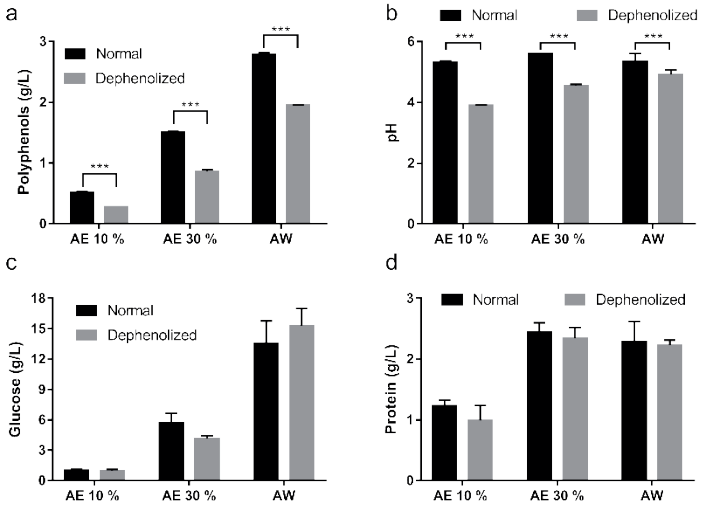

Fig. 1. Some physicochemical characteristics of the mediums used for *Rh. mucilaginosa* growth.

2.2 *Rh. mucilaginosa* growth and carotenoid production in the different mediums

We next studied the growth of *Rh. mucilaginosa* in the different mediums (Fig. 2). In AE 10 %, yeast reaches the stationary phase at 2 days, and no lag period is detected, probably due to the sampling period used. Both curves (Normal and dephenolized) are almost superimposed, thus dephenolization does not affect *Rh. mucilaginosa* growth, indicating that this phenol concentration is not inhibitory for the yeast. However, in AE 30 % and AW, a significantly higher number of cells are produced when the yeast grew in dephenolized mediums, being this effect more evident in AE 30%. In both dephenolized mediums, the stationary phase is reached at 1 day, and an acceleration of cell division is observed. Interestingly, when dry weight is measured, different behavior is observed. Changes are only detected in AW, where dephenolization increases the mass of yeast obtained. Although it is clear that dephenolization favors *Rh. mucilaginosa* development, the phenol content and yeast growth, (measured as the number of cells or dry weight) are not linearly related. Indeed, the same number of cells are obtained in all dephenolized mediums despite the differences in phenol content. Interestingly, dry weight increase in 30 % AE and in dephenolized AW respect with 10 % AE. This could be explained considering that in these mediums cells are accumulating reserve substances like triglycerides and/or carotenoids. *Rhodotorula* yeasts are known for its ability to produced these compunds [9]. In dephenolized AW, for instance, that has slightly higher phenol content than AE 30 %, we obtained threefold the number of yeast. Thus, other factors may influence yeast development in these complex mediums.

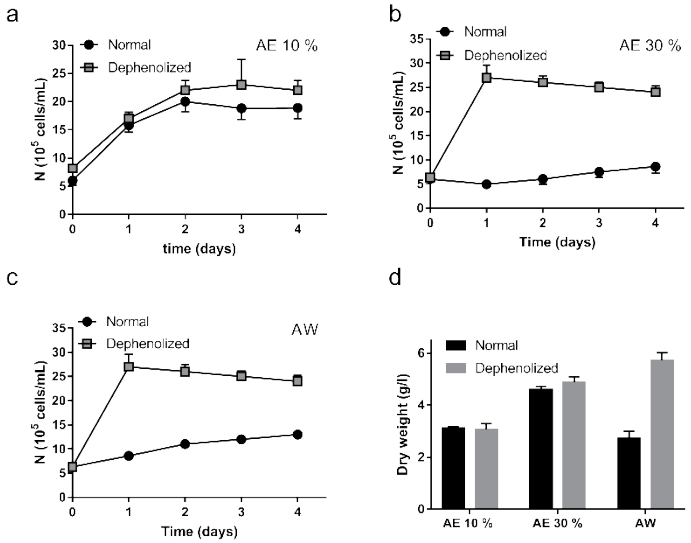

Fig. 2. Kinetics of *Rh. mucilaginosa* growth in different mediums.

Total carotenoid production was also affected by dephenolization. As shown in Fig. 3, the total carotenoid volumetric production increases when *Rh. mucilaginosa* starts

the stationary phase. This is expected since carotenoids are secondary metabolites. In AW and AE 30 % dephenolization result in a higher carotenoid production. This effect is more evident in AW, where dephenolization not only increases carotenoid amounts but also the pattern of production. In normal AW a plateau is reached at 3 days where for dephenolized AW, carotenoid production continues even at 4 days.

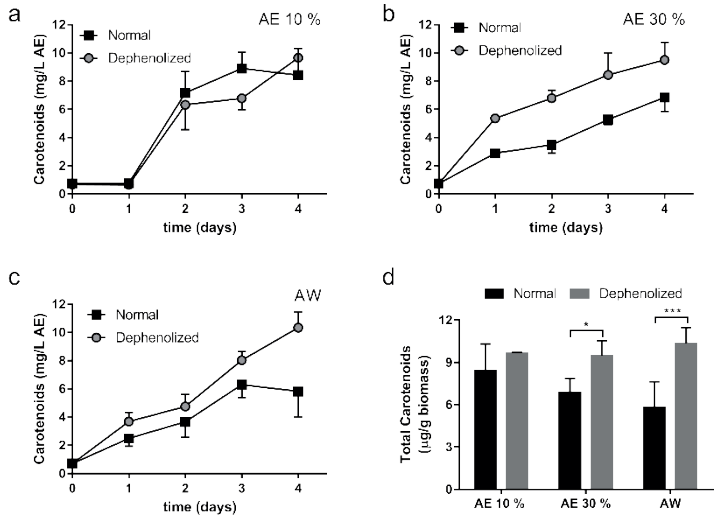

Fig. 3. Carotenoid production in different mediums.

3 Materials and Methods

3.1 Microorganism:

Rh. mucilaginosa was kindly provided by the Instituto de Botánica "Carlos Spegazzini" and it was maintained in agar slants at 4 °C until required.

3.2 Two-phase olive mill waste (TPOMW) samples and culture medium preparation:

Arbequina fresh TPOMW samples were provided by an oil processing plant located in Coronel Dorrego, province of Buenos Aires (Argentina). The samples were stored at -20 ºC until further use. Alperujo Water (AW) was obtained by centrifuging fresh alperujo at 1372g for 20 min. The liquid phase was separated, filtered and sterilized by autoclaving at 120 ºC for 15 min. Aqueous extracts (AE) were prepared from freeze-dried and defatted alperujo in concentrations of 10 and 30 % (w/V) as in [10]. To prepare dephenolized mediums, a volume of culture medium (AW, AE:10% and 30%) was mixed with ethyl acetate in a 3:1 ratio and polyphenols were extracted at 25 °C, with

magnetic stirring for 2h. Two successive extractions were performed. Upon completion, the content was transferred into a 250 mL separation funnel and the aqueous phase (i.e. the dephenolized medium) was collected in a 250 mL beaker. The remaining ethyl acetate was evaporated under a nitrogen stream at room temperature.

3.3 Analytical procedures:

Total phenolic content was determined spectrophotometrically at 725 nm according to the Folin-Ciocalteu method using caffeic acid as standard (Gutfinger 1981). Glucose was measured with an enzymatic-Glicemia kit, kindly provided by Wiener Lab (Rosario, Argentina). The pH was measured with an Altronix TPX-I electrode. Protein was determined by the Lowry method (Lowry et al. 1951) previous precipitation with trichloroacetic acid. Dry cell weight was determined at 85 °C using a Kern DLB 160-3A thermobalance (Kern, Germany). The number of yeasts was counted in a Neubauer chamber using an inverted microscope Zeiss Primo Star (Carl Zeiss, Germany).

3.4 Production, extraction, and quantification of carotenoids:

Cultures were performed in 250 mL Erlenmeyer flasks containing 50 mL of the desired concentration of AE and incubated for 4 days at 30 ºC under orbital shaking (150 rpm). Samples were taken on days 0, 1, 2, 3, and 4. To measure glucose, total phenolics, pH and biomass, 2 mL of culture were removed under sterile conditions. The medium was centrifugated at 1372 g for 15 min, the biomass separated and the supernatant was filtrated and stored at -20 ºC until required. The carotenoids were extracted using a custom-manufactured laboratory ball mill (Electronics Laboratory and Turning - Metallurgy UAT, Conicet Bahía Blanca). Briefly, freeze-dried biomass samples (~ 20 mg) were weighed in 1.5 mL Eppendorf tubes and 3 stainless-steel balls of 5 mm diameter were added. Three consecutive grinding cycles were performed, at 25 Hz and 60 seconds long each. Finally, 500 µL of acetone was added and a final grinding cycle was carried out. Then, the tubes were left to stand for 30 minutes in dark and centrifuged at 15.000 g for five minutes at 4 ºC. Quantification was performed by measuring absorbance at 450 nm in a Shimadzu UV-160A spectrophotometer. A calibration curve was prepared with β-carotene in acetone and the result was expressed as β-carotene equivalents. Each culture condition was run in triplicate.

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Gelificación del caseinomacropéptido en presencia de sales de calcio (cloruro de calcio y acetato de calcio)

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Resumen. El caseinomacropéptido (CMP) es un péptido abundante en el suero de queso. El acetato de calcio ($CaAc_2$) es una de las sales más prescriptas en EE.UU para el tratamiento de la hiperfosfatemia. El objetivo de este trabajo fue explorar la interacción entre el CMP y las sales de calcio ($CaCl_2$ y $CaAc_2$) a través de la dinámica de gelificación inducida por calentamiento a pH 3,5. Interpretar cómo interacciona el CMP con los iones calcio permitirá desarrollar formulaciones que permitan mejorar la funcionalidad de los suplementos dietarios de sales de calcio. Se evaluó la textura, el color y las características reológicas de los geles formados, tanto a temperatura ambiente como por calentamiento, y se analizaron los correspondientes espectros FTIR. La transparencia de los geles en presencia de 100 mM de $CaCl_2$ o $CaAc_2$ se debería a la formación de unidades estructurales de menor tamaño que interaccionan con el calcio. A pH 3,5, se favorece termodinámicamente la formación de calcio iónico cuando se utiliza $CaAc_2$. Asimismo, los cambios observados en los espectros FTIR del CMP en presencia de $CaAc_2$ y más marcadamente con $CaCl_2$, confirmarían una estructura molecular más ordenada. La relación de saturación sal/CMP encontrada fue 0,83 mmoles/g, sin embargo, los geles admiten concentraciones mayores de $CaCl_2$ o $CaAc_2$. Por consiguiente, la formación de geles de CMP y sales de calcio a pH 3,5 podría ser una excelente alternativa para vehiculizar calcio iónico, si se utiliza $CaAc_2$ para el tratamiento de la hiperfosfatemia.

Palabras clave: caseinomacropéptido, acetato de calcio, gelificación

1 Introducción

El caseinomacropéptido (CMP) es un péptido abundante en el suero de quesería. Constituye la porción hidrofílica C-terminal de la κ-caseína y contiene todas las modificaciones postraduccionales (glicosilación y fosforilación) presentes en ella [1]. Naturalmente es mezcla heterogénea de dos fracciones principales: glicosilada (gCMP), y

no glicosilada (aCMP) [2]. Se identificaron catorce formas glicosiladas para el CMP [3] en las cuales el carbohidrato más abundante es el ácido N–acetilneuroamínico (ácido siálico) [4], que tiene un valor de pKa de 2,2. Debido a su alta heterogeneidad, el CMP no tiene un único punto isoeléctrico (pI). Kreuß et al. [2] determinaron que el pI del aCMP es cercano a 4,15, relacionado con la abundancia de residuos ácidos en su cadena peptídica. En contraste, el pI del gCMP es 3,15, debido a la carga negativa de los residuos glicosilados y en especial del ácido siálico que reducen su carga neta [2].
A pH 3,5, el CMP se autoensambla con el tiempo por la reducción de la repulsión electrostática y finalmente gelifica a temperatura ambiente [5]. Es por ello que resulta una proteína ideal para la nanoencapsulación, sólo o en combinación con otras proteínas. Recientemente, Bourbon et al. [6] realizaron nanohidrogeles de CMP y lactoferrina, una proteína láctea catiónica transportadora de hierro. La nanoencapsulación o el desarrollo de sistemas de entrega a nanoescala de compuestos bioactivos presenta interés por sus funcionalidades, alta eficiencia y capacidad de carga, la mejora de la biodisponibilidad y estabilidad, además de un perfil de liberación sostenida y el enmascaramiento de sabores indeseables [7]. Interpretar cómo interacciona el CMP con los iones calcio permitirá desarrollar formulaciones que permitan mejorar la funcionalidad de los suplementos dietarios de sales de calcio.
El acetato de calcio ($CaAc_2$) es una de las sales más prescriptas en EE.UU para el tratamiento de la hiperfosfatemia en pacientes sometidos a diálisis por su función como quelante de fosfatos [8, 9]. El CMP podría facilitar la ingesta de la gran cantidad de $CaAc_2$ prescripta para un paciente con hiperfosfatemia, aumentando tanto la bioaccesibilidad como la palatabilidad.
El objetivo de este trabajo fue explorar la interacción entre el CMP y las sales de calcio ($CaCl_2$ y $CaAc_2$) a través de la dinámica de gelificación inducida por calentamiento a pH 3,5. Se evaluó la textura, el color y las características reológicas de los geles formados, tanto a temperatura ambiente como por calentamiento, y para interpretar cómo afecta este pH (3,5) a las interacciones entre el CMP y el calcio, se analizaron los correspondientes espectros FTIR.

2 Materiales y métodos

2.1 Materiales

Se utilizó caseinomacropéptido BioPURE-GMP® de Davisco Foods International (USA). Su pureza, según el proveedor, fue (en base seca): 90,0 ± 3,0% (p/p) de CMP (N x 7,07). Su contenido mineral fue (100 g de muestra): 950 mg de Na; 125 mg de K y 682 mg de Ca determinados mediante espectrometría de absorción atómica Analyst 200 Perkin Elmer (USA). Se utilizó $CaCl_2$ anhidro (Merck, Alemania) y $CaAc_2$ monohidratado (Merck, Alemania) de calidad analítica. El agua utilizada para preparar las soluciones fue ultrapura (Thermo Scientific Barnstead, modelo Easypure RF) y su conductividad fue 1,8 ± 0,1 μS/cm. El pH de todos los sistemas se ajustó a 3,5 con HCl 1 N para evitar dilución.

2.2 Métodos

2.2.1. *Preparación de las soluciones.* Se utilizó una concentración de CMP del 12% (p/p) como en trabajos previos [10, 11] con el objeto de acelerar los tiempos de gelificación. Las soluciones de CMP se prepararon como en Loria et al. [12] hasta alcanzar la concentración de sal deseada (entre 0 y 250 mM) de $CaCl_2$ o $CaAc_2$. El CMP es muy soluble en agua y no se formó ningún precipitado después de añadir las soluciones salinas.

2.2.2. *Transición sol-gel*. El tiempo de transición solución-gel se determinó por un test de inclinación modificado o "tilting test" [13]. Las soluciones de CMP al 12% y a pH 3,5 se calentaron en tubos de ensayo cerrados a temperatura constante entre 30 y 70ºC y se observaron en el tiempo. Se determinó el tiempo de gelificación (t_{til}) como aquel necesario para que el menisco de la solución contenida en los tubos no fluya al inclinarlo. Los valores reportados fueron la media de triplicados.

2.2.3. *Dinámica de gelificación y propiedades viscoelásticas de los geles.* La dinámica de gelificación se registró en un reómetro de esfuerzo de corte controlado Paar Physica (MCR 301, Graz, Austria) con una geometría de cono y plato PP25 con un gap de 1 mm. Inmediatamente luego de ajustar el pH, se vertieron 490 µl de solución en el plato del reómetro. Se eligió la temperatura de 70ºC con el objeto de acelerar los ensayos según Martinez et al. [14]. El ensayo duró 40 minutos, tiempo suficiente para permitir que G' alcance el equilibrio. Luego se enfrió el sistema a 25ºC en 10 min.
Las propiedades viscoelásticas del gel formado se midieron en función de la frecuencia de oscilación entre 0,05 y 10 Hz a 25 ºC con la misma deformación, 0,01% [11]. Se informó el módulo complejo, que describe la relación entre la deformación y el esfuerzo a través de la siguiente ecuación:

$$G^* = G' + i\,G'' \quad (1)$$

donde, G' es el módulo de almacenamiento o elástico; G" es el módulo de pérdida o viscoso.

2.2.4. *Color y Textura de los geles.* Los geles de CMP y diferentes concentraciones de $CaCl_2$ o $CaAc_2$ (10 ml) se formaron a temperatura ambiente en recipientes herméticos y cilíndricos de plástico de 2,5 cm de diámetro y 4 cm de altura. Los geles se almacenaron 24 hs bajo refrigeración antes de realizar los ensayos de color y textura. Como los geles de CMP no se autosoportaron, estos ensayos se realizaron en el mismo recipiente en el cual fueron preparados.
La medición del color en unidades CIELAB (L*, a*, b*) de las muestras se realizó con un colorímetro portátil MiniScan® EZ (Hunter Lab, Reston, VA, USA). El escaneo de cada muestra se realizó 3 veces, obteniendo los parámetros del color L*, a* y b*. Las determinaciones se realizaron por cuadriplicado. La diferencia de color después y antes de la gelificación se calculó con la siguiente ecuación:

$$\Delta E = [\Delta L^2 + \Delta a^{*2} + \Delta b^{*2}]^{1/2} \quad (2)$$

donde ΔL es la diferencia de luminosidad; Δa* es la diferencia de intensidad de color verde/rojo y Δb* es la diferencia de intensidad de color azul/amarillo después y antes de gelificar.
El análisis de perfil de textura (TPA) se realizó a 25ºC en un analizador de textura Texture Analyzer (modelo TA-XT2i; Stable Microsystems, Godalming, Reino Unido) usando una sonda cilíndrica de ebonita (P/05 1,27 cm de diámetro). Las muestras se comprimieron al 20% de la altura inicial con una velocidad de compresión de 0,5 mm s^{-1}. Los ensayos se realizaron por cuadriplicado.

2.2.5. *Espectroscopía FTIR*. Las muestras en solución fueron almacenadas en freezer a una temperatura de -80ºC durante 24 hs y posteriormente liofilizadas (Labconco® freezone 12). Los espectros fueron registrados a temperatura ambiente en un espectrofotómetro infrarrojo Shimadzu® (modelo IR Prestige-21, Japón) en un rango de longitud de onda de 4000 nm^{-1} a 500 nm^{-1}. Se utilizó 1 mg de muestra liofilizada mezclada con 100 mg de KBr, pulverizada en un mortero de ágata y luego presionada a 20 Bar para obtener una pastilla. Cada muestra se sometió a 40 scans con 2,0 cm^{-1} de resolución. El registro de datos se realizó con el software LabSolution IR®, y el análisis de los espectros y los picos con el software OriginPro® 8 SR0, V8.0724, USA.

2.2.6. *Análisis estadístico.* Se utilizó el software GraphPad Prims v7.0 (GraphPad Software, San Diego, CA, USA) para el análisis estadístico. Los datos fueron analizados a través de un análisis de varianza (ANOVA). Las diferencias fueron determinadas por la prueba de Tukey para $P < 0,05$.

3 Resultados y discusión

3.1. Transición sol-gel

Martinez et al. [14] demostraron que el CMP se autoensambla a temperatura ambiente a valores de pH inferiores a 4,5. Estas estructuras autoensambladas conducen, con el tiempo, a la formación de geles opacos dependiendo de los tiempos de gelificación de la concentración. A concentraciones tan bajas como 3% (p/p), a pH 3,0 o 3,5 los tiempos necesarios para la gelificación son tan largos como 6-15 días, pero para concentraciones superiores a 7-8% (p/p), el tiempo se acorta (<50 h) [5]. Otro factor que afecta drásticamente a la velocidad de gelificación es la temperatura. Calentar desde 25ºC hasta 60ºC produce un aumento en las velocidades de autoensamblaje y gelificación. Por encima de 60 ºC ambas velocidades permanecen constantes [10, 14]. Con el propósito de investigar la temperatura óptima para la gelificación de las soluciones de CMP en presencia de $CaCl_2$, se determinó el tiempo de transición sol-gel a través del ensayo de "tilting test". Se evaluó el tiempo de gelificación (t_{til}) y la velocidad de gelificación ($V_{til} = 1/t_{til}$) de las muestras de CMP 12% (p/p) con concentraciones variables de $CaCl_2$ (0 - 250 mM) a diferentes temperaturas (30-70ºC). La Fig. 1A muestra la gráfica de Arrhenius, donde se representa el lnVtil en función de la inversa de la temperatura absoluta (1/T). Las curvas mostraron un comportamiento lineal entre 30 y 60ºC, y un quiebre a partir de esa temperatura. Hasta los 60 ºC, V_{til} dependió sólo de la

temperatura independientemente de la cantidad de $CaCl_2$ presente en la muestra. Por encima de los 60ºC, V_{til} fue constante y tampoco se hallaron diferencias por la presencia de $CaCl_2$.

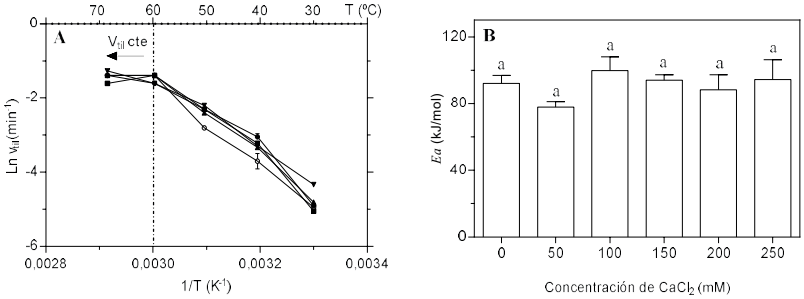

Fig. 1 A) Gráficos de Arrhenius para las velocidades de gelificación (V_{til}) de soluciones de CMP al 12% (p/p) y diferentes concentraciones de $CaCl_2$: (○) 0 mM; (▼) 50 mM; (■) 100 mM; (▲) 150 mM; (●) 200 mM a pH 3,5. **B)** Energía de activación (E_a) en función de la concentración de $CaCl_2$. Las barras de error representan el desvío estándar (n=3). Letras diferentes indican diferencias significativas ($p<0,05$).

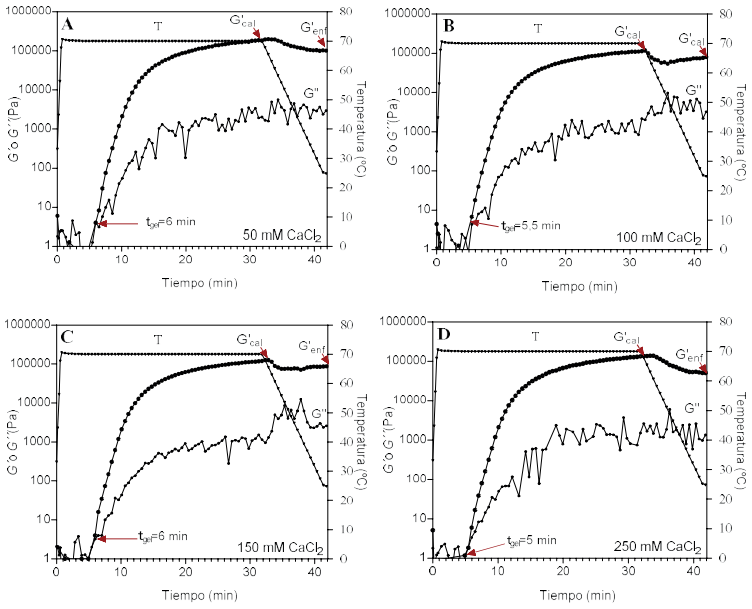

Fig. 2 Evolución de G' (●) y G'' (■) durante la gelificación de soluciones de CMP 12% (p/p) y $CaCl_2$ (50 - 250 mM) a pH 3,5 y 70ºC.

Se determinaron las energías de activación (E_a) involucradas en la gelificación de los sistemas CMP/$CaCl_2$ mediante la ecuación de Arrhenius. Las pendientes de las rectas obtenidas multiplicadas por la constante universal R corresponden a la E_a, que se muestra en la Fig.1 B en función de la concentración de $CaCl_2$. El valor de E_a promedio determinado en el rango 30-60ºC fue de 91 ± 8 kJ/mol y no fue afectado por la presencia de $CaCl_2$. Estos valores fueron relativamente bajos en comparación con la gelificación de aislado de proteína de suero (WPI) inducida por acidificación (pH 4,0) con glucano-δ-lactona (155 kJ/mol) o por $CaCl_2$ (210 kJ/mol) [15]. Con el propósito de reducir los tiempos de gelificación, se gelificó a las soluciones a la temperatura de 70ºC, donde V_{til} fue independiente de la temperatura.

3.2. Dinámica de gelificación

La Fig. 2 muestra la dinámica de gelificación inducida por calor de las soluciones (CMP 12% p/p y $CaCl_2$ entre 50 y 250 mM) a pH 3,5. El cruce de los módulos elástico (G') y viscoso (G'') indicó el tiempo (t_{gel}) y temperatura de gelificación (70ºC) [16]. Se puede observar en la Fig. 2 un solo punto de gel (t_{gel}) a 5,4 ± 0,5 min que no fue afectado por la concentración de $CaCl_2$. Los valores de t_{gel} hallados por esta metodología estuvieron en el orden de los encontrados por la técnica del tilting test, aunque en este último caso fueron mayores porque el ensayo del "tilting" requiere de una estructura que soporte el gel [17].

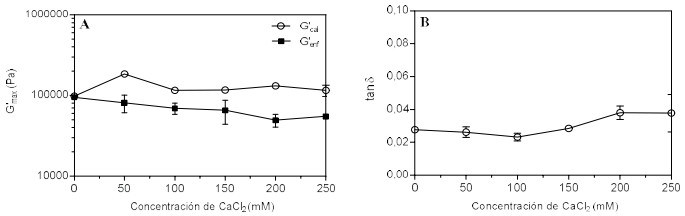

Fig. 3 A) Evolución de G'_{cal} (○) y G'_{enf} (■) durante el calentamiento y enfriamiento de geles de CMP 12% (p/p) con $CaCl_2$ (0 - 250 mM) a pH 3,5. **B)** Evolución de tan δ de los geles a pH 3,5 y 25ºC.

En el reograma del CMP en ausencia de $CaCl_2$ (datos no mostrados) se evidenciaron dos puntos de gel (t_{gel1}=1 min y t_{gel2}=6,5 min) como fue descripto en [14] a pH 3,5. Este comportamiento se atribuye a la existencia de dos estructuras que gelificaron a diferentes tiempos. Según el modelo de gelificación [14], el CMP gelifica en dos etapas en ausencia de sales y a pH 3,5. La primera es la formación de dímeros a través de uniones hidrofóbicas y la segunda, es la formación de una estructura de gel a través de interacciones electroestáticas. A pH 3,5, la fracción no glicosilada del CMP (aCMP) está protonada (pI = 4,15) [2], por lo cual los dímeros de aCMP-aCMP tienen carga positiva. En cambio, los dímeros de la fracción glicosilada gCMP-gCMP tienen carga negativa (pI = 3,15) [2]. Una situación intermedia se da para los dímeros aCMP-gCMP. Por lo tanto, a pH 3,5 coexisten dímeros cargados positivamente que contienen aCMP y

dímeros cargados negativamente que contienen gCMP que interactúan electrostáticamente. La existencia de dos puntos de gel en los reogramas del CMP a pH 3,5 se explicaría por los posibles estados isoeléctricos de los dímeros [14]. Por consiguiente, la presencia de $CaCl_2$ (aún a baja concentración) afectó principalmente a las estructuras que gelificaban primero y determinaban el t_{gel1}.

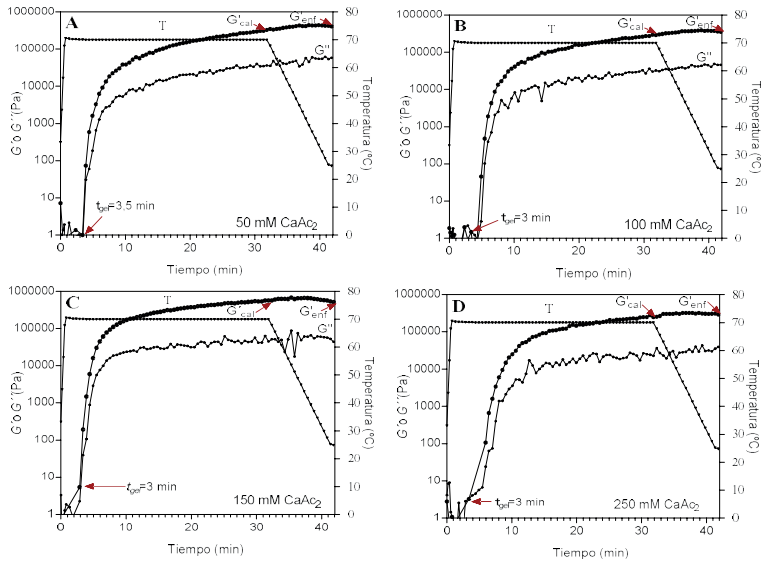

Fig. 4. Evolución de G' y G'' durante la gelificación de CMP (12 % p/p) con $CaAc_2$ (50-250 mM) a pH 3,5 y 70ºC.

Los reogramas obtenidos en el estudio de la gelificación del CMP en presencia de $CaAc_2$ (50; 100; 150 y 250 mM) a pH 3,5 se muestran en la Fig. 4. En todos los casos se encontró un único punto de gel en aprox. 3 min. Se puede observar que a diferencia de los geles en presencia de $CaCl_2$, G' se desarrolló muy rápidamente luego del punto de gel. Aún a bajas concentraciones de $CaAc_2$, G'_{enf} superó a G'_{cal}. Por otro lado, las diferencias entre G'_{enf} y G'_{cal} no fueron significativas. Pero es de destacar que todos los sistemas con CMP/$CaAc_2$ presentaron un desarrollo de G' con valores 3 veces superiores a los de CMP a fuerza iónica nula.

Si bien G'_{cal} no varió significativamente con la concentración de $CaCl_2$, G'_{enf} presentó una tendencia decreciente (desde 95.000 Pa en ausencia de sal, hasta 55.000 Pa en presencia de 200 y 250 mM de $CaCl_2$). Luego del t_{gel}, los valores de G' siempre fueron superiores a los de G''. El valor de G' máximo alcanzado durante el período de calentamiento fue denominado G'_{cal} y el G' obtenido al final del enfriamiento G'_{enf}. En la Fig. 3A se realiza un análisis detallado mostrando que G'_{cal} y G'_{enf} discrepan en su valor en presencia de $CaCl_2$, aún a bajas concentraciones (50 mM), evidenciando que en el enfriamiento disminuyeron ligeramente las interacciones de las estructuras gelificadas.

La tangente del ángulo de fase δ (tan δ) es un indicador de la organización estructural de un material. Los valores de tan δ (G" /G') obtenidos al finalizar el período de enfriamiento (25 ºC) fueron similares en todos los sistemas y claramente muy bajos (0,03 – 0,04), sugiriendo un arreglo de red elástica (Fig. 3B). Por ejemplo, la tan δ de la gelatina es 0,03 [18]. Se puede visualizar que los valores de tan δ fueron similares independientemente de la concentración de $CaCl_2$ adicionada al CMP.
La dinámica de gelificación del CMP en presencia de $CaAc_2$ a pH 3,5 y 70 ºC (Fig. 4), mostró que las sales influyeron en todos los parámetros reológicos: el tiempo de gelificación, en los módulos G' y G" y en la tan δ. Los tiempos de gelificación en presencia de $CaCl_2$ fueron independientes de la concentración y más largos (aprox. 6 min), mientras que, en presencia de $CaAc_2$ se redujeron a la mitad. Los geles con $CaCl_2$ mostraron una disminución de G´ durante la etapa de enfriamiento, en cambio los geles con $CaAc_2$ mostraron un ligero incremento. La tan δ de estos últimos fue 0,12 ± 0,01 independientemente de la concentración de $CaAc_2$ y superior a aquella obtenida para el CMP en ausencia de sal (0,03). Un valor de tan δ más alto indica que el material responde a la tensión externa en un modo más viscoso y menos elástico. Evidentemente, la presencia de $CaAc_2$ alteró la estructura del gel de CMP. El anión acetato consolida las fuerzas atractivas en los geles de CMP, mientras que el anión cloruro las disminuye durante el enfriamiento.

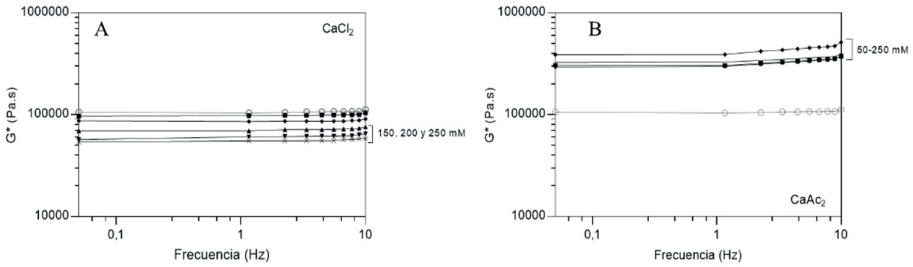

Fig. 5. G* en función de la frecuencia de oscilación para geles de CMP a pH 3,5 con A) $CaCl_2$ y B) $CaAc_2$ con (○) 0 mM; (●) 50 mM; (◆) 100 mM; (■) 150 mM; (▲) 200 mM y (▼) 250 mM (n=2 o 3).

3.3. Propiedades de los geles de CMP en presencia de $CaCl_2$ o $CaAc_2$.

3.3.1. Pequeñas deformaciones.

En el rango de frecuencia analizado (0 a 10 Hz), no se observó dependencia con la frecuencia para ambos módulos (G' y G") en los espectros mecánicos del CMP en presencia de $CaCl_2$ o $CaAc_2$. G' fue siempre superior a G". Los valores de G' fueron aproximadamente 110.000 Pa para los geles con 0, 50 y 100 mM de $CaCl_2$, 76.000 Pa para 150 mM y 56.000 Pa para 200 y 250 mM $CaCl_2$. Se encontró una tendencia similar en G" cuyo valor también disminuyó, desde 4.000 Pa a 3.000 Pa, para 200 y 250 mM

de $CaCl_2$ (datos no mostrados). En los geles de CMP/$CaCl_2$, el módulo complejo (G*) fue independiente de la frecuencia de oscilación para todos los sistemas (Fig. 5A). G* disminuyó desde $7{,}0.10^4$ hasta $5{,}5.10^4$ Pa en presencia de $CaCl_2$ (150-250 mM).
Los barridos de frecuencia de los geles de CMP en presencia de $CaAc_2$ también mostraron el típico comportamiento de gel fuerte, donde G' fue siempre superior a G" y no se observaron entrecruzamientos en la frecuencia estudiada. La Fig. 5B muestra que G* fue independiente de la frecuencia de oscilación para los geles de CMP/$CaAc_2$. Los valores de G* fueron superiores en presencia de $CaAc_2$ por el mayor aporte viscoso de G". Por otro lado, los valores de tan δ fueron cercanos a 0,15, relacionados con el incremento del carácter viscoso del gel (aumento de G") (datos nos mostrados).

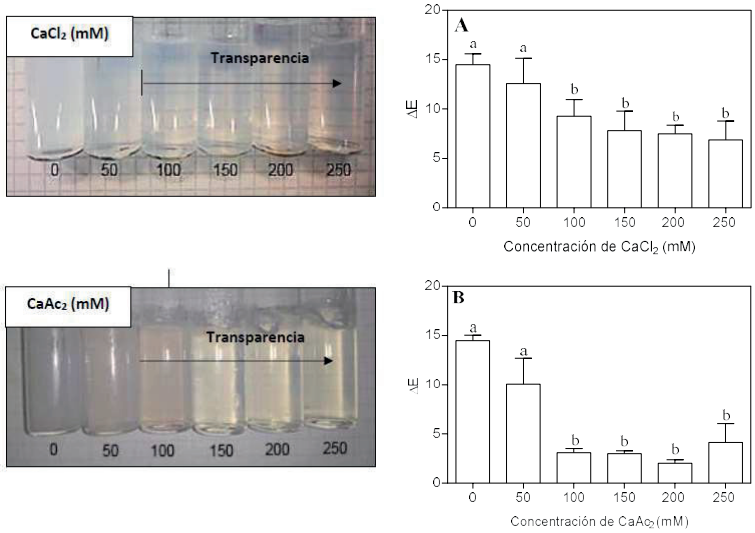

Fig. 6. Izq.) Imágenes de los geles de CMP con $CaCl_2$ o $CaAc_2$ a pH 3,5, formados a 70 ºC y enfriados a 25 ºC. Der.) Diferencia de color (ΔE) de los geles de CMP 12% (p/p) antes y después de gelificar a pH 3,5, formados a 25ºC, con: **A)** $CaCl_2$, **B)** $CaAc_2$.

3.3.2. Parámetros del color

Los geles de CMP formados en ausencia de sales fueron opacos a pH 3,5 como fue informado en Farías y Pilosof [11]. En presencia de $CaCl_2$ o $CaAc_2$ los geles se tornaron transparentes a partir de concentraciones superiores a 100 mM (Fig. 6). La temperatura de formación de los geles no afectó a su coloración como se informó previamente en Farias [19] para geles de CMP a pH 2 a 3,5 en condiciones de fuerza iónica nula. Ninguno de los geles obtenidos fueron desmoldables. En todo momento los recipientes se mantuvieron sellados herméticamente para evitar la evaporación del agua. La **Fig. 6** muestran el cambio de los parámetros de color (L*, a* y b*) de las muestras de CMP a pH 3,5 antes y después de la gelificación a temperatura ambiente y la apariencia de los

geles. La medición del color corroboró la observación visual. Los resultados mostraron que los geles de CMP con $CaCl_2$ o $CaAc_2$ presentaron resultados similares a partir de la concentración de 100 mM o superior. Dado que la concentración de los geles fue de 12% (p/p), la relación de sal de calcio por gramo de CMP fue 0,8 mmoles calcio/g. Evidentemente, el agregado de las sales de calcio provocó cambios en el tamaño de los agregados que conforman la estructura del gel, haciéndolos más transparentes.

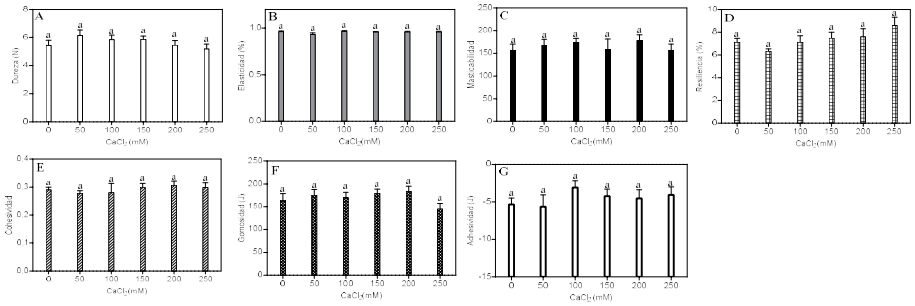

Figura 7. Parámetros de textura **A)** Dureza, **B)** Elasticidad, **C)** Masticabilidad, **D)** Resiliencia, **E)** Cohesividad, **F)** Gomosidad y **G)** Adhesividad de geles de CMP 12% (p/p) a diferentes concentraciones de $CaCl_2$ formados a 25 ºC y a pH 3,5.

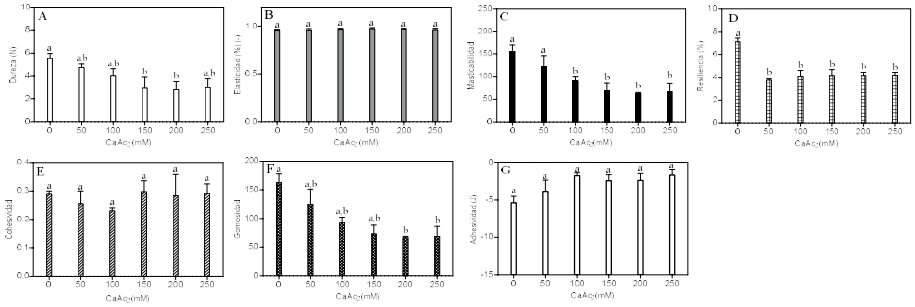

Fig. 8. Parámetros de textura **A)** Dureza, **B)** Elasticidad, **C)** Masticabilidad, **D)** Resiliencia, **E)** Cohesividad, **F)** Gomosidad y **G)** Adhesividad de geles de CMP 12% (p/p) a diferentes concentraciones de $CaAc_2$ formados a 25 ºC y a pH 3,5.

3.3.3 Parámetros de textura

Las propiedades texturales de los geles de CMP no dependieron de la temperatura en la que se formaron [11, 19]. Los parámetros texturales obtenidos del ensayo TPA (Texture Profile Analysis) fueron dureza, elasticidad, masticabilidad, resiliencia, cohesión, gomosidad y adhesividad (Fig. 7 y 8). La Fig. 7A muestra que no se encontraron diferencias significativas ($p < 0,05$) en la dureza de los geles de CMP en presencia de $CaCl_2$ (≈ 6 N). Por otro lado, la dureza de los geles de CMP disminuyó hasta aproximadamente 4 N en presencia de $CaAc_2$ (Fig. 7B). La elasticidad denota cómo el gel se recupera luego de ser deformado. Los resultados mostraron que los geles de CMP fueron muy elásticos con un valor muy cercano a 1%, independientemente del tipo o concentración de sal incorporada al CMP (Fig. 7B y 8B). La masticabilidad, que es el producto entre la dureza, la cohesividad y la elasticidad, fue similar para los geles de CMP en presencia de $CaCl_2$ (Fig. 7C). Sin embargo, los geles con $CaAc_2$ presentaron valores más bajos a concentraciones superiores a 100 mM (Fig. 8C). La resiliencia fue relativamente baja en todos los geles, con valores de 7 – 9% para los geles de CMP con $CaCl_2$ (Fig. 7D) y valores aún más bajos, (4 – 6%) con $CaAc_2$ (Fig. 8D). La cohesividad es la propiedad que mide la recuperación del gel luego de la segunda deformación. Los geles de CMP no presentaron diferencias significativas con la incorporación de $CaCl_2$ o $CaAc_2$ y tuvieron un valor de ≈ 0,3 (Fig. 7 y 8E). La gomosidad, que es el producto entre la dureza y la cohesividad, se define como la energía requerida para romper un alimento semisólido antes de tragarlo [20]. La gomosidad de los geles de CMP fue cercana a 150 a fi nula o en presencia de $CaCl_2$ (Fig. 7 F). Sin embargo, este parámetro disminuyó a valores cercanos a 100 en presencia de $CaAc_2$ (Fig. 8F). Finalmente, en cuanto a la adhesividad, se observó que todos los geles tuvieron un valor despreciable (Fig. 7 y 8G).

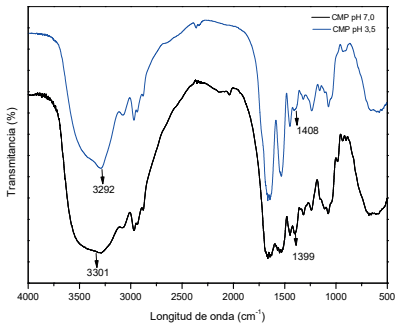

Fig. 9 Espectro FTIR del CMP a pH 7 y 3,5 (4000 - 500 cm^{-1}).

3.1 Espectroscopía infrarroja por transformada de Fourier (FTIR)

En la Fig. 9 se muestra el espectro completo FTIR del CMP a pH 3,5. La banda ancha de alta intensidad de absorción (Amida 2º A) se desplazó desde 3301 a 3292 cm^{-1} al disminuir el pH desde 7,0 a 3,5. La zona de vibración (1700 - 1600 cm^{-1}) correspondiente a la Amida I (tensión del enlace C=O, tensión del enlace C-N y flexión del enlace N-H) mostró un profundo valle y además de otros picos (1643, 1664 y 1674 cm^{-1}) con

respecto a los hallados en el espectro del CMP a pH 7,0 (1649 y 1655 cm^{-1}). El autoensamblaje y gelificación del CMP a pH 3,5 evidentemente establecería un cierto orden estructural del cual carece el péptido a pH 7,0 de conformación "random coil". La señal de la Amida I es el mejor indicador de la estructura secundaria de una proteína [21]. La región de Amida II (flexión de los enlaces N-H y C-N) también es indicativa de cambios en la estructura secundaria de las proteínas, sin embargo, también es muy sensible a la hidratación [22]. La señal correspondiente a los grupos COO^-, que en el CMP a pH 7,0 se observó a 1399 cm^{-1} se desplazó a 1408 cm^{-1} a pH 3,5. Un desplazamiento de esta señal fue encontrada por Ustunol et al. [23] para el ácido glutámico en las asignaciones de las vibraciones de los COO^- a pH 2 (1410 cm^{-1}) en comparación a los pH entre 6 y 9 (1401 cm^{-1}).

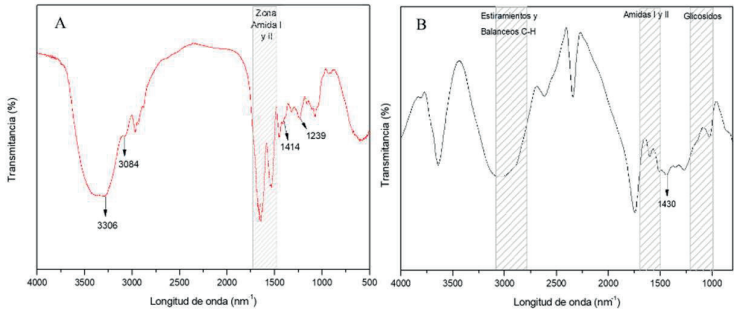

Fig. 10. Espectro FTIR del CMP con A) $CaCl_2$ y B) $CaAc_2$ (relación 1,2 mmoles de $CaCl_2$/g CMP) a pH 3,5.

El espectro FTIR del CMP y $CaCl_2$ en la relación 1,2 mmoles de $CaCl_2$/g CMP se muestra en la Figura 10A. La banda de absorción de Amida 2º A, que en el CMP a pH 3,5 se ubicó a 3292 cm^{-1}, se desplazó a 3306 cm^{-1} en presencia de $CaCl_2$ con una señal más intensa y la banda de Amida 2º B desde 3077 cm^{-1} a 3084 cm^{-1}. En la zona de absorción de la Amida I (1700 - 1600 cm^{-1}) y Amida II (1600 - 1500 cm^{-1}) se observaron nuevos picos a 1628 - 1636 cm^{-1} y 1539 - 1548 cm^{-1}, respectivamente. Interesantemente, estos nuevos picos (1628 y 1636 cm^{-1}), se asignan a una estructura secundaria β-plegada [22]. Además, en presencia de $CaCl_2$, la absorbancia de la Amida I decreció, mientras que la de la Amida II se incrementó. Estos cambios estarían asociados al decrecimiento de la estructura "random coil" y el incremento de una estructura más organizada (β-plegada), como fue explicado por Villarreal-Ramirez et al. [24] para fosfopéptidos obtenidos de la dentina. El pico correspondiente a la señal de la Amida III (1236 cm^{-1}) a pH 3,5 se desplazó ligeramente a 1239 cm^{-1} en presencia de $CaCl_2$. El pico a 1408 cm^{-1}, que representa el estiramiento simétrico de los COO^- a pH 3,5, se desplazó a 1414 cm^{-1} en el espectro CMP/$CaCl_2$, sugiriendo que estos grupos interaccionan con calcio iónico a pH 3,5. Además, aparecen dos bandas a 1548 y 1539 cm^{-1}. Byler y Farrell [25] demostraron que el corrimiento de las bandas a 1410 y 1565 cm^{-1} son indicadoras de una interacción de las proteínas con el calcio iónico.

La Figura 10B muestra el espectro de CMP con $CaAc_2$ a pH 3,5. Se encontraron una gran cantidad de señales solapadas entre 3250 y 3000 cm^{-1} que corresponderían

principalmente a estiramientos y balanceos de las uniones C-H. Tambien se observó un solapamiento de muy alta intensidad en la zona de amida I (1700 - 1600 cm^{-1}) y amida II (1600 - 1500 cm^{-1}). Por otro lado, no se observó señal a 1408 cm^{-1} (estiramientos simétricos de los COO^-) y también cambió la zona del espectro en la zona de la huella digital (1300-400 cm^{-1}). Problablemente, los solapamientos observados se deban a las interferencias de los grupos funcionales con el anión acetato. A pH 3,5, las fracciones del CMP tienen cargas opuestas, por lo tanto puede interactuar electrostáticamente tanto el $CaAc^+$, el Ca^{2+} como el Ac^-. Cabe recordar aquí que la gelificación se realizó ajustando el pH a 3,5 con HCl de alta normalidad, por lo tanto el desplazamiento del Ac^- para formar HAc permite la liberación de Ca^{2+}. El espectro del CMP en presencia de $CaAc_2$ es diferente a los observados anteriormente confirmando una naturaleza más compleja en las interacciones.

4. Conclusiones

El efecto de las sales de calcio en la gelificación del CMP a pH 3,5 es muy complejo debido a que interaccionan tanto el catión como el anión con los diferentes estados eléctricos de las diversas fracciones del péptido. Evidentemente, el anión acetato consolida las fuerzas atractivas en los geles de CMP, mientras que el anión cloruro las disminuye durante el enfriamiento. A pH 3,5, se favorece termodinámicamente la formación de calcio iónico cuando se utiliza $CaAc_2$, como lo muestran los espectros FTIR y la coloración de los geles. Asimismo, los cambios observados en los espectros FTIR del CMP en presencia de $CaAc_2$ y más marcadamente con $CaCl_2$, confirmarían una estructura molecular más ordenada. La relación de saturación sal/CMP encontrada de 0,83 mmoles/g fue independiente del tipo de sal utilizada y ligeramente menor que a pH 7 (1,2 mmoles/g). La formación de geles de CMP y sales de calcio a pH 3,5 podría ser una excelente alternativa para vehiculizar calcio iónico, si se utiliza $CaAc_2$ para el tratamiento de la hiperfosfatemia porque los geles al 12% (p/p) admiten concentraciones de $CaCl_2$ o $CaAc_2$ hasta 250 mM.

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Evaluación composicional de bagazo de diferentes estilos de cerveza artesanal para su valorización

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Abstract. El grano agotado de cebada malteada (bagazo) obtenido de la elaboración de cerveza, es uno de los subproductos más abundantes de la industria cervecera y es rico en compuestos bioactivos, fibras, proteínas y aceite. Si bien en la actualidad el bagazo se utiliza principalmente para alimentación animal, su rico contenido nutricional lo convierte en una alternativa interesante para su utilización en formulaciones alimentarias. Sin embargo, este residuo, actualmente no ha sido muy estudiado. El objetivo del presente trabajo, fue realizar una comparación de bagazos, obtenidos a partir de la elaboración de distintos estilos de cerveza artesanal (Dorada, Scottish y Hazy APA), realizando una caracterización proximal y una posterior caracterización funcional de los componentes presentes en dichos subproductos. Los resultados obtenidos mostraron diferencias significativas entre los bagazos. Los principales componentes de la caracterización fueron, fibras estructurales (como fibra detergente neutro, FDN) y proteína bruta. La proteína bruta presentó una variación entre 13,61 y 22,30% en base seca (b.s.), dependiendo el bagazo y la FDN entre 36,92 y 46,87 %b.s. y libre de grasa. El contenido de aceite osciló entre 1,9 y 5,0 %b.s., siendo el componente minoritario. En la caracterización funcional se determinó la digestibilidad de las fibras y la solubilidad de las proteínas, donde se observó que los residuos de maltas Dorada presentaron una mayor digestibilidad, indicado por la relación fibra:proteína y por la menor proporción de hemicelulosa en su composición. Por otra parte, los residuos de malta Dorada también presentaron, mayor solubilidad de las proteínas otorgándole mejores características funcionales.

Palabras claves: grano gastado, bagazo de cerveza, fibras, proteínas.

1 Introducción

La industria alimentaria genera anualmente grandes cantidades de desechos agroindustriales en todo el mundo a partir del procesamiento y la fabricación de alimentos y bebidas [1]. Los subproductos y desechos de los alimentos están formados por componentes altamente complejos, muchos de los cuales pueden tener un alto valor

como proteínas, polisacáridos, fibras, saborizantes, fitoquímicos, etc. Estos pueden ser extraídos, purificados, y caracterizados por las tecnologías existentes y emergentes, lo que conduce al desarrollo de nuevas aplicaciones comerciales en sectores alimentarios y no alimentarios como la industria farmacéutica, biomédica, cosmética, etc. [2,3]. Los cereales, sus derivados y los efluentes provenientes de su industrialización, son considerados especialmente atractivos como materia adecuada debido a su abundancia y disponibilidad [4,5].

La cerveza es una bebida alcohólica que resulta de fermentar, mediante levadura seleccionada, el mosto de cebada malteada, sola o mezclada con otros productos amiláceos (adjuntos). Todas las cervezas se elaboran con cuatro ingredientes básicos que son: malta, agua, levadura y lúpulo, pero se diferencia según el proceso de elaboración en cerveza artesanal y cerveza industrial, las calidades de los ingredientes y en la fórmula que el maestro cervecero ha creado [5,6]. Puede contener otros granos de cereales malteados como trigo, centeno o sorgo, o sin maltear como arroz, maíz e incluso cebada, dependiendo del tipo de cerveza que se produce. La malta es el ingrediente más significativo y el que le confiere color a la cerveza, así como también contribuye al aroma, al sabor, y al cuerpo de la misma. Las diferentes maltas aportan azúcares, los cuales la levadura fermentará posteriormente. A su vez, la espuma de la cerveza obtiene estructura gracias a las proteínas de los granos de los distintos tipos de malta.

La elaboración de cerveza produce varios residuos que incluyen: granos agotados (bagazo), lúpulo agotado y levaduras agotadas. Por cada 100 litros de cerveza elaborada, se generan aproximadamente, un 14-20 kg de grano agotado durante el filtrado y 0,2-0,4 kg de lúpulo agotado, generado durante la ebullición del mosto y la adición del lúpulo (por la coagulación y formación de complejos de proteínas de alta masa molar y compuestos fenólicos oxidados). Además, la levadura residual es el resultado de la multiplicación celular durante la fermentación [7].

El bagazo, correspondiente a la parte insoluble del grano de cebada germinada, es el subproducto más abundante generado a partir del proceso de elaboración de la cerveza. Después del proceso de maceración, el grano agotado es desechado y representa alrededor de un 85 % del total de subproductos obtenidos. Su composición puede variar según la variedad de grano empleado, su época de cosecha, las condiciones de malteado y maceración, y la calidad y tipo de complementos agregados al proceso de elaboración. Durante la elaboración de cervezas, en general se utiliza la combinación de dos o tres tipos de maltas y otros adjuntos para lograr los diferentes estilos. El grano agotado contiene alrededor de un 30-50 % de fibra, 19-30 % de proteína y 2-10 % de lípidos [8].

A nivel industrial todos los residuos son agrupados como un único residuo y son los responsables de las pérdidas en el proceso de elaboración de la cerveza, proporcionando pérdidas de mosto, extracto y también cerveza, según de qué fase se extraiga el residuo, lo que conduce también a la generación de cantidades significativas no solo de residuo sólido, sino también de efluentes líquidos [7]. Actualmente, este residuo es utilizado principalmente como alimento animal, pero también presenta otros usos como producción de biocombustibles y etanol, biogás, materiales de construcción, materiales de fabricación de papel y adsorbentes, entre otros. También, se han realizado varios intentos para emplear el grano agotado en la producción de compuestos de valor agregado (xilitol, ácido láctico, etc.), cultivo de microorganismos o simplemente como

materia prima para la extracción de compuestos como azúcares, proteínas, ácidos, antioxidantes y en la producción de enzimas [9]. Sin embargo, estos usos han sido poco estudiados aún.

La composición del grano agotado de la cebada hace que este material resulte atractivo para la industria de alimentos, pudiendo proporcionar recursos proteicos verdes, innovadores y de alta calidad, que podrían satisfacer las necesidades de salud de los seres humanos [8]. En este contexto, una de las principales áreas de explotación de este tipo de residuos sería la recuperación de componentes valiosos como materias primas para la obtención de productos de valor agregado. Las proteínas del bagazo posiblemente se puedan utilizar como fuente proteica, no solo para animales, sino también en la dieta humana. Los hidrolizados de proteínas han sido, durante algún tiempo, el punto focal de la investigación nutritiva, ya que se ha demostrado que los hidrolizados de proteínas de fuentes vegetales, tienen efectos antiinflamatorios y actividad antioxidante [10,11]. Por otra parte, el material lignocelulósico del bagazo está constituido por una estructura compleja de celulosa, hemicelulosa y fibras de lignina.

La utilización de estos residuos por parte de los grandes productores de cerveza (industrial) ha sido investigada, sin embargo, el conocimiento acerca de la utilización de éstos entre los cerveceros artesanales (*craft brewers*) es incipiente [7,11]. Para una evaluación adecuada del bagazo, como fuente de productos de valor agregado, y su potencial aplicación en tecnologías de bioprocesos, la caracterización de los diferentes componentes presentes es de gran interés. Sin embargo, estudios previos se han ocupado principalmente de la composición y obtención de carbohidratos, lignina, y ácidos p-hidroxicinámicos del bagazo cervecero, y en menor medida de la composición y obtención de lípidos y proteínas. A pesar de los estudios existentes, aún no existen antecedentes sobre la comparación entre los bagazos provenientes de diferentes estilos de cervezas, los cuales podrían diferir significativamente en su composición y calidad, debido a que los distintos estilos de cervezas son elaborados con diferentes tipos de maltas [13-15]. En el presente trabajo se realizó una comparación de la composición de diferentes bagazos, obtenidos de la elaboración de distintos estilos de cerveza artesanal y posteriormente se analizó la funcionalidad de los componentes mayoritarios (fibras estructurales y proteínas).

2 Materiales y métodos

Los bagazos se obtuvieron de la elaboración de cervezas realizadas por la cátedra de Laboratorio de Procesamiento de Alimentos, del Departamento de Ingeniería Química (UNS). Los tipos de cervezas empleados fueron Dorada, Scottish y Hazy APA (American Pale Ale) y en la Tabla 1 se resumen las especificaciones de las maltas utilizadas en su elaboración. Los bagazos fueron secados en un secadero rotativo con aire a 60°C, hasta alcanzar un contenido de humedad menor al 14%, para acondicionarlos hasta su reutilización.

Se determinó en los bagazos secos el contenido de humedad, lípidos, proteínas, fibra detergente neutra (FDN), fibra detergente ácida (FDA) y hemicelulosa.

El contenido de humedad se determinó según técnica IUPAC 1.121 [16], por secado en estufa de vacío a 100 ºC hasta peso constante. La determinación del contenido de aceite

se llevó a cabo en un equipo Soxhlet, empleando n-hexano grado comercial como solvente, siguiendo la norma IUPAC 1.122 [16]. El contenido de proteína cruda se determinó utilizando el método de Kjeldahl [17], empleando un digestor y destilador Büchi. Para el análisis de las fibras estructurales, se siguió el método de Van Soest [18]. Este método de análisis separa la pared celular del contenido celular y sus componentes: celulosa, hemicelulosa y lignina. Empleando un simple balance se calculó el contenido de hemicelulosa entre el valor de FDN y FDA.

Tabla 1: Tipos de maltas y adjuntos según el estilo de cerveza**.**

Maltas	**Tipo**	**Temperatura de horneado (°C)**	**Dorada**	**Scottish**	**Hazy APA**
Base	Pilsen	80-85	x	x	
	Pale	80-85			x
	Munich	100-108			x
	Trigo	80			
	Viena	90-100	x		
Especiales	Caramelo 60	64-71		x	
	Chocolate	220		x	
Adjuntos	Copo de Trigo				x
	Copo de Avena	---			x

El contenido de humedad y lípidos fue expresado en base seca (% b.s.) y el contenido de FDN, FDA, hemicelulosa y proteínas se expresó en base seca desgrasada (% b.s.d). Por otra parte, se realizó una caracterización funcional de los residuos, determinando la digestibilidad de la materia seca (DMS), la energía digestible (ED) y la energía metabolizable (EM), a través de estimaciones en las muestras desgrasadas, según ecuaciones de predicción de National Research Council (N.R.C.,1998). El porcentaje de DMS fue determinado por la ecuación predictiva (1) a partir del contenido de FDA [19]:

$$\%DMS = 88{,}9 - 0{,}779\ \%FDA \quad (1)$$

El contenido de energía metabolizable (EM) del residuo fue estimado, según las normas inglesas de alimentación [20] con la siguiente ecuación (2):

$$EM = 3{,}61\ \%DMS \quad (2)$$

La caracterización funcional se realizó sobre las proteínas y las fibras. La solubilidad de las proteínas se determinó en función del pH, las muestras se dispersaron en agua destilada con una relación sólido:líquido de 1:20. El pH de las suspensiones se ajustó a los valores de: 1,4; 3,6; 4,5; 5,7; 7,1; 10,1 y 12,3 utilizando HCl 0,1 M y NaOH 0,1 M. Las suspensiones se agitaron durante 1 hora a temperatura ambiente y se midió su pH. Los contenidos de proteínas en los sobrenadantes, obtenidos después de la centrifugación (3115 g; 25 min), se determinaron por el método colorimétrico de Lowry, calibrado con una curva estándar de albúmina de suero bovino (BSA). La

solubilidad de las proteínas se expresó como el porcentaje de proteína soluble extraído en relación contenido total de proteína presente en los distintos bagazos [21-22].

2.2. Análisis estadístico

El análisis estadístico de los resultados se llevó a cabo por medio del Análisis de Varianza (ANOVA) usando el software Infostat [23]. La comparación de medias se realizó mediante el test de Tukey con un nivel de significancia de $p \leq 0,05$.

3 Resultados y discusión

3.1. Determinación del contenido de humedad, lípidos y proteínas.

La Tabla 2 presenta el contenido de humedad final de las diferentes muestras (luego del secado). Las mismas presentaron valores menores a 11 % b.s. El bajo contenido de humedad permitió mantener la estabilidad de los materiales y la calidad microbiológica para su posterior uso.

Tabla 2: Contenido de humedad, lípidos y proteínas de los bagazos en estudio.

Bagazos	Humedad (% b.s.)	Aceite (% b.s.)	Proteínas (% b.s.d*)
Dorada 1	10,8 ± 0,10	1,94 ± 0,05[a]	16,23 ± 0,16[a]
Dorada 2	11,6 ± 0,07	2,05 ± 0,03[a]	15,25 ± 0,15[b]
Scottish	7,81 ± 0,09	3,01 ± 0,14[b]	18,26 ± 0,18[c]
Hazy APA	3,37± 0,03	4,68 ± 0,07[c]	23,02 ± 0,23[d]

Los datos son valores medios ± error estándar n=3. Los valores en la misma columna con la misma letra no son significativamente diferentes (p>0,05) por método Tukey.
*b.s.d: base seca desgrasada.

El contenido de aceite osciló entre el 2 y 5 % en peso del bagazo seco (b.s.). El análisis estadístico arrojó diferencias significativas entre las maltas Doradas respecto de la Scottish y Hazy APA ($p < 0,05$). Los valores encontrados en bibliografía presentan una amplia variabilidad en la composición lipídica, con valores que llegan hasta un 10 % b.s. de lípidos totales. Faulds et al. [13] reportaron un contenido de lípidos similares a los presentados en este trabajo para la malta Hazy APA (5,4 % b.s.). Del Rio et al. [24], por su parte, reportaron un contenido de lípidos de 9,2 % b.s., un valor superior, pero acorde a valores informados previamente en otros documentos [5,25,26]. Esta variabilidad en el contenido de lípidos, depende principalmente de las distintas variedades de maltas en cada residuo. A pesar del contenido de lípidos de dichos residuos, los estudios sobre la composición de los mismos, aun son relativamente escasos y limitados.

El contenido de proteínas presentó diferencias significativas para todos los residuos analizados ($p < 0,01$). Los residuos de malta Dorada 1 y Dorada 2 fueron los que presentaron el menor contenido, con valores de 13,6 % y 14,7 % b.s.d, respectivamente. Otros autores han reportado contenidos de proteínas, con valores de 22-24 %,

presentando concordancia con los resultados obtenidos para el residuo de malta Hazy APA [25-28]. Esta variabilidad en la composición, depende principalmente del uso de diferentes maltas y del proceso al que fueron sometidas. Cada residuo derivado de un estilo de cerveza, es elaborado con una o más variedades de maltas, las cuales son el producto del grano germinado bajo condiciones controladas. Esta germinación modifica la composición química del grano, produciendo cambios en la composición del mismo. El grado de transformación durante el malteado se conoce como modificación y es debidamente controlado con el manejo de las condiciones de crecimiento a las cuales es expuesto el grano. Los cambios esenciales que ocurren durante la modificación del grano son tres, comenzando con el aumento en la cantidad de enzimas hidrolíticas presentes en el grano, mediante liberación o síntesis; la degradación de las paredes celulares, gomas, proteínas y almidón por parte de estas enzimas y, por último, una reducción en la fuerza estructural del tejido del grano. Las cervezas con diferentes sabor, color, aroma, suavidad y espuma utilizan maltas producidas por estos diferentes procesos, que en particular difieren principalmente en el tiempo y temperatura de secado y tostado posterior al malteado. Estas etapas desarrollan sabor y color de diferentes grados de intensidad para la preparación de diferentes cervezas [29].

3.2. Determinación del contenido de fibras estructurales

El bagazo cervecero es de naturaleza lignocelulósica. Los polisacáridos en el bagazo están representados por celulosa (formada por unidades repetitivas de b-D-glucopiranosa) y hemicelulosa (heteropolímero formado por azúcares no celulósicos como manosa, xilosa, galactosa y arabinosa) y comprenden casi el 45 % del peso seco total. La lignina, un polímero ramificado, forma el resto de la composición del bagazo [5,29].
Los cuatro residuos analizados presentaron un contenido de FDN (celulosa, hemicelulosa y lignina) entre 36 % y 48 % (Tabla 3). Según el análisis estadístico, los residuos de bagazos de Doradas fueron significativamente diferentes respecto de los de Scottish y Hazy APA ($p<0,05$). Sin embargo, los bagazos de Doradas presentaron menor contenido de fibra que lo reportado hasta el momento en bibliografía [26,30].

Tabla 3: Contenido de FDN, FDA y Hemicelulosa de los cuatro bagazos analizados.

Bagazo	FDN (% b.s.d)	FDA (% b.s.d)	Hemicelulosa (% b.s.d)
Dorada 1	$42,04 \pm 0,42^{a}$	$14,91 \pm 0,14^{a}$	$27,13 \pm 0,27$
Dorada 2	$41,20 \pm 0,41^{a}$	$16,13 \pm 0,16^{b}$	$25,07 \pm 0,25$
Scottish	$48,03 \pm 0,48^{b}$	$17,73 \pm 0,17^{c}$	$30,30 \pm 0.30$
Hazy APA	$49,41 \pm 0,49^{b}$	$18,93 \pm 0,18^{d}$	$30,48 \pm 0,30$

Los datos son valores medios ± error estándar n=2. Los valores en la misma columna con la misma letra no son significativamente diferentes ($p>0,05$) por método Tukey. *b.s.d: base seca desgrasada.

Por otra parte, se encontraron valores similares a los de Hazy APA, en otros trabajos previos. Yu et al [26] reportaron un contenido de fibra detergente neutra de 51,0 ± 0,7 % y Shen et al. [30] obtuvieron valores de 46,6 %.

Mussato et al. [31] asociaron las diferencias en la composición del bagazo, no solo a los diferentes tipos de maltas sino también al país de producción y al proceso de elaboración de cerveza y concluyó que independientemente de las variaciones reportadas en la cantidad de cada constituyente en la composición del bagazo, este material está compuesto principalmente de fibras (celulosa, hemicelulosa y lignina) y proteínas (como se muestra en la Tabla 3). La hemicelulosa y la celulosa son fracciones constituidas por azúcares, siendo los más abundante en el bagazo la xilosa, la arabinosa y la glucosa. Los azúcares corresponden a aproximadamente la mitad de la composición del bagazo en peso seco, lo que representa una fracción muy importante.

En comparación con otros productos agroindustriales, el bagazo presenta un contenido elevado de hemicelulosa, más alto que el que presentan otros subproductos de cultivos, incluyendo cáscara de arroz, de trigo, cebada y avena. Por otra parte, el bagazo presenta menor contenido de celulosa, pero posee un contenido de lignina similar frente a estos subproductos.

3.3. Estimaciones de digestibilidad de la MS (DMS), energía digestible (ED) y energía metabolizable (EM)

Desde un punto de vista económico y ambiental, se ha hecho un esfuerzo por encontrar una reutilización del residuo generado durante la elaboración de la cerveza. El bagazo cervecero es el subproducto más abundante de la industria de la cerveza y aunque tiene un bajo costo, hasta el momento, sus aplicaciones son muy limitadas. Actualmente, se lo utiliza en alimentación animal a pesar de su alto valor, principalmente como fuente de moléculas bioactivas. El contenido de fibra en el forraje juega un papel muy importante dentro de la alimentación y nutrición de ganado bovino y rumiantes en general. La calidad y cantidad de fibra afectan la capacidad de consumo voluntario y la cantidad de energía que puede aportar una ración [32]. A medida que el forraje madura, aumenta su contenido de fibra detergente neutra, lo cual determina una más lenta tasa de digestión con mayor tiempo de retención ruminal. En términos prácticos, la fibra detergente neutra es inversamente proporcional a la capacidad de consumo que los animales tendrán sobre ese alimento (a más FDN, menor consumo voluntario). Las determinaciones de FDA, buscan cuantificar las fracciones de celulosa y lignina del alimento. Al igual que en el caso anterior, estos compuestos se incrementan con el avance de los estadios fenológicos de las forrajeras. Ello implica una correlación negativa con la digestibilidad de la materia seca y un menor contenido energético aprovechable [33].

La Tabla 4 muestra las estimaciones de digestibilidad de la materia seca (DMS), la energía digestible (ED) y la energía metabolizable (EM). Para la realización de las estimaciones fue necesario conocer el contenido de FDN y FDA (Tabla 2).

Tabla 4: Estimaciones de digestibilidad de la MS (DMS), energía digestible (ED) y energía metabolizable (EM) de diferentes tipos de bagazos de cerveza.

Bagazos	**DMS %**	**ED** Mcal/kg MS	**EM** Mcal/kg MS
Dorada 1	78,44	3,45	2,83
Dorada 2	77,68	3,42	2,81
Scottish	76,09	3,36	2,75
Hazy APA	74,61	3,30	2,71

La digestibilidad es una forma de medir el aprovechamiento de un alimento, en otras palabras, es la facilidad con que el alimento es convertido en el aparato digestivo en sustancias útiles para la nutrición. Comprende dos procesos, la digestión correspondiente a la hidrólisis de las moléculas complejas de los alimentos, y la absorción de pequeñas moléculas, como aminoácidos y ácidos grasos, en el intestino. La digestibilidad, a su vez, puede constituir un indicador de calidad de la materia prima que a veces varía notablemente, de una especie a otra; a priori deberían esperarse valores muy distintos en las especies carnívoras, herbívoras u omnívoras [34]. Independientemente de la metodología utilizada para evaluar la calidad, se considera que un subproducto tiene alta calidad cuando tiene aproximadamente 70 % de digestibilidad de la materia seca (DMS) o más, menos de 50 % de fibra detergente neutra (FDN) y más de 15 % de proteína bruta (PB) [20]. De acuerdo a lo mencionado, se puede observar que los residuos de malta Scottish y Hazy APA podrían ser considerados de alta calidad. Mientras que los bagazos obtenidos de las maltas Dorada, presentan un menor contenido de proteínas. Cuando se ofrece un residuo con menor contenido de proteínas y elevado contenido de fibras, existe una depresión parcial en la digestión de la fibra. La digestibilidad es afectada por varios factores, siendo la fibra cruda el principal componente que afecta de manera negativa la digestibilidad de un insumo o dieta. Por otra parte, los mayores valores de energía digestible se presentan para los bagazos de maltas Dorada, según algunos autores esto se explica por la menor cantidad de fibra cruda presente en el residuo [35].

El contenido de energía digestible (ED), correspondiente a cada una de los residuos estudiados, se consignan en la Tabla 4, donde se observa que la energía digestible de los residuos de maltas Doradas fueron los valores superiores a los encontrados entre todos los residuos. Los mayores valores de energía digestible de los residuos de malta dorada, en comparación a los demás bagazos, podría ser explicado por la menor cantidad de fibra presente en las mismas (36,9 y 37,8 %) y posiblemente por una mayor cantidad de extracto libre de nitrógeno, en este caso, la energía es mejor aprovechada [35]. Por otra parte, cabe destacar que todos los valores de energía digestible fueron superiores a los informados por otros autores para distintos forrajes, los cuales no superan valores de 2,5 Mcal/kg MS. Esto podría dar indicio de la calidad de los residuos estudiados, los cuales presentan ciertas características (tanto nutricionales como funcionales) que hacen del bagazo un buen subproducto de valor agregado.

La energía metabolizable (EM), es la cantidad de energía retenida por el organismo para las diferentes necesidades, y se utiliza en la actualidad como unidad básica para expresar los valores energéticos de los alimentos y las necesidades del animal [36]. La energía metabolizable presentó valores similares en todos los residuos, estos valores se encuentran en concordancia con los reportados por otros autores para diferentes subproductos utilizados en alimentación animal [36].

3.4. Solubilidad de las proteínas

La solubilidad de las proteínas es una de las propiedades fisicoquímicas y funcionales más importantes. El grado de solubilidad de las proteínas varía en función de diversos factores: pH, concentración salina, temperatura, etc. En general las proteínas globulares son solubles en agua debido a los radicales R que están colocados en la superficie de la proteína y que establecen enlaces por puente de Hidrógeno con el agua. Varios investigadores han demostrado que la mayoría de las proteínas vegetales tienen la solubilidad proteica más baja en su punto isoeléctrico y luego aumenta hacia los valores de pH básicos. En general, las proteínas del bagazo son poco solubles en agua (menos del 10 %) [37].

En el presente trabajo, el estudio de solubilidad se realizó modificando el pH del medio desde 1,5 hasta 12,3. En un perfil típico de solubilidad proteica en agua en función de pH, se observó que la solubilidad es máxima a pHs muy ácidos (2-3) o muy alcalinos (9-11). En dichas zonas, las proteínas poseen cargas neta positivas o negativas, respectivamente y las fuerzas repulsivas son la causa del incremento en su solubilidad. También fue posible observar un mínimo de solubilidad en las cercanías del pH isoeléctrico (pI), a pH=3-5 (dependiendo el tipo de muestra), donde la carga neta de las proteínas es cero, por lo que disminuye la repulsión electrostática y se promueve la agregación [22].

La Fig. 1 muestra la solubilidad de las proteínas, expresada como porcentaje, g Proteína solubles/100 g de proteínas totales, de los distintos bagazos en función del pH. En todos los casos, la menor solubilidad se obtuvo a valores de pH inferiores a 4. Al aumentar el pH a valores superiores, se produjo la precipitación consecutiva de las proteínas, encontrándose que los residuos de maltas Dorada, a un pH de 4,2, son casi completamente insolubles (0,206 y 0,335 % b.s., Dorada 1 y 2, respectivamente). Luego en cercanías del pH neutro, la solubilización de las proteínas se vio favorecida, presentando un aumento significativo a valores superiores a 5. A pH alcalino se observó que alrededor de un 25-35 % del total de las proteínas de los bagazos, pueden solubilizarse en agua. Por otra parte, se pudo determinar que el punto isoeléctrico fue a pH cercanos a 3,6 para todas las muestras. Este valor se encuentra en concordancia con los reportados por Arauzo et al. [38] y Connolly et al. [39] para proteínas de bagazo.

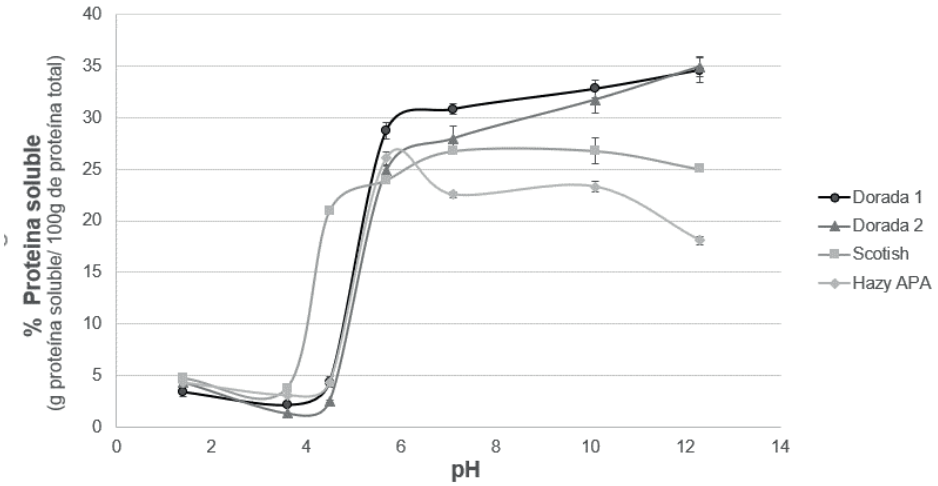

Fig. 1: Perfil de solubilidad de las proteínas de cuatro bagazos obtenidos de la elaboración de tres estilos de cerveza artesanal.

Los residuos de malta Dorada presentaron un aumento significativo de la solubilidad de las proteínas cuando el pH aumentó a 5,7, en ambos residuos. A partir de este pH, el aumento de la solubilidad fue menos significativo con el ascenso de pH hasta valores de 12,3. El residuo de bagazo de Dorada 1, incrementó la solubilidad de las proteínas en un 6 % pasando de un pH de 5,7 a 12,3. Mientras que el residuo de bagazo de Dorada 2 presentó un incremento del 10 % para un mismo intervalo de pH. Por su parte, el residuo de Scottish presentó su menor solubilidad a pH 3,4 con un 4 % de proteína solubilizada, mientras que alcanzó su máxima solubilización a pH 7,1 (28,8 %) no observándose variación con un aumento de pH hasta 12,3. El residuo de bagazo de Hazy APA, presentó la menor solubilidad de las proteínas a un pH de 3,5, mientras que el aumento significativo de solubilidad se alcanzó a un pH de 5,7 alcanzando un 27 % de solubilización del total de la proteína presente en la muestra, a partir de este pH la curva se vuelve asintótica para dicho residuo.

Si bien, el residuo de Hazy APA presentó el mayor contenido de proteína bruta, la solubilidad de la misma fue menor que para el resto de los residuos. Los residuos de maltas Doradas contenían proteínas con una solubilidad significativamente mayor que los demás bagazos. También se pudo observar que las proteínas del bagazo Scottish mostraron una mayor solubilidad sobre el rango de pH más ácido. Algunos autores consideran un pH de 3,8-4,0 como el pH de precipitación para la recuperación de proteínas de bagazo extraídas con álcali [22,39].

El aumento de la solubilidad de las proteínas podría estar afectado por la versatilidad de las muestras y por los diferentes tratamientos a los que se sometieron las maltas previo uso en la elaboración de las cervezas. Por otra parte, el aumento de la solubilidad

de las proteínas puede deberse, también, a la disminución de peso molecular y al despliegue de proteínas. Tanto los grupos de aminoácidos no polares como algunos polares, encerrados dentro de las moléculas de proteínas, podrían quedar expuestos en la superficie de las moléculas después del despliegue. Estos aminoácidos polares expuestos pueden interactuar con las moléculas de agua a través de enlaces de hidrógeno e interacciones electrostáticas, lo que resulta en un aumento de la solubilidad proteica [22].

Para aumentar las aplicaciones potenciales de las proteínas insolubles, se podría aplicar hidrólisis química y enzimática. La hidrólisis enzimática es leve y no destruye los aminoácidos. Los efectos sobre las propiedades nutricionales, aun resultan poco estudiados. Además, las enzimas son específicas en su acción y esto permite un procesamiento controlado. Los hidrolizados formados por diversas enzimas pueden tener diferentes funcionalidades. La hidrólisis de proteínas cambia el peso molecular, la carga y la exposición de grupos hidrófobos, además de las cadenas laterales reactivas de aminoácidos. Estas transformaciones moleculares resultan en cambios en la solubilidad, viscosidad, propiedades sensoriales y comportamiento emulsionante y espumante de las proteínas [22].

4 Conclusiones

Los esfuerzos crecientes hacia la reutilización de subproductos agroindustriales, tanto desde el punto de vista económico como ambiental han ido en aumento en los últimos años. El bagazo es un subproducto abundante producido en cervecerías de todo el mundo. Sin embargo, a pesar de la amplia gama de posibles aplicaciones, todavía se restringe su uso y actualmente, es utilizado principalmente como alimento para animales.

En el presente trabajo se pudo realizar una comparación de distintos bagazos obtenidos a partir de diferentes estilos de cervezas artesanales, realizando una caracterización proximal y una posterior caracterización funcional de fibras y proteínas. Los residuos presentaron una amplia gama de componentes y diferencias en la funcionalidad de los mismos. En este estudio se observó que los bagazos provenientes de diferentes estilos de cervezas no presentaron una misma composición y dependiendo del tipo de malta utilizada, se diferenciaron tanto en la cantidad como en la funcionalidad de los componentes. Este estudio podría contribuir a la búsqueda de potenciales usos de los bagazos discriminando los residuos según su composición para potenciar su empleo. El conocimiento de dichos componentes y su funcionalidad resultan de gran interés para la industria de alimentos. Desde el punto de vista nutricional, el alto contenido de fibra y proteína del bagazo lo hace muy interesante para su aplicación en la dieta humana, tanto en aplicaciones alimentarias como en biotecnológicas. Este subproducto también podría representar una valiosa fuente de componentes bioactivos.

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Inactivación de *Fusarium graminearum* en cebada cervecera (*Hordeum vulgare* L.) mediante ozono en fase acuosa: potencial aplicación en la etapa de malteado

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Resumen. La presencia de mohos en la cebada cervecera representa un inconveniente para la industria maltera, debido a la pérdida de calidad de esta materia prima en cuanto a sus propiedades tecnológicas y de inocuidad por la presencia de micotoxinas. El ozono (O_3) es una tecnología emergente que puede aplicarse para la reducción de la carga microbiana de esta matriz. La etapa de remojo en el proceso de malteado proporciona condiciones favorables para el tratamiento de los granos de cebada con ozono en fase acuosa. El objetivo de este trabajo fue evaluar el efecto de la aplicación de diferentes dosis de ozono en fase acuosa sobre la inactivación fúngica en cebada cervecera contaminada artificialmente con *Fusarium graminearum*, utilizando una columna de burbujeo a escala de laboratorio. Se realizaron tratamientos de ozonización en una etapa (a diferentes tiempos de exposición) y en tres etapas (durante 45 min por etapa) a 20 ± 1 °C, y se determinó su efecto sobre el porcentaje de granos infectados, incubados a 15, 20 y 25 °C. Los resultados se compararon con controles de lavado, además del control. El tratamiento con ozono en 3 etapas redujo significativamente la contaminación de *F. graminearum*, evidenciándose el efecto positivo de la ozonización con respecto a sólo el proceso de lavado cuando la incubación se realizó a 20 y 25 °C. A 15 °C no hubo un efecto adicional significativo del ozono sobre el efecto mecánico del lavado.

Palabras clave: Cebada, Malteado, Ozono, Contaminación fúngica

1 Introducción

Uno de los principales ingredientes en el proceso de fabricación de la cerveza es la malta, que se obtiene a través del malteado de la cebada cervecera. Mediante el malteado se logra un grano de cebada rico en enzimas, con una estructura del endospermo que permite la hidrólisis del almidón, el cual será la fuente de energía de las levaduras durante la fermentación [1, 2]. En el proceso industrial de malteado, la cebada cervecera, al ser recibida en la maltería, pasa por un proceso de limpieza y clasificación, y luego es almacenada en silos. Las etapas siguientes son el remojo, la germinación y el secado. Durante el remojo de la cebada, se sumergen los granos en agua (36-52 h a 12-20 °C) para aumentar el contenido de humedad del grano hasta un nivel que permita su germinación (alrededor de 45%); esta etapa involucra varios pasos de inmersión en agua (en condiciones aerobias) seguidas de descansos para aireación. Posteriormente se elimina el agua de remojo y se lleva a cabo la germinación de los granos en una atmósfera de aire humidificado (15-20 °C). Durante esta etapa ocurren diversas modificaciones bioquímicas y morfológicas en los granos, evidenciadas por la formación de raicillas. Para detener la germinación, los granos se secan con aire caliente (hasta 90 °C) hasta alcanzar un 5% de humedad. Es en esta etapa donde se definen el color, aroma y sabor de la malta. Finalmente se eliminan las raíces y se almacena la malta [2].

La contaminación de la cebada cervecera por hongos filamentosos (mohos), principalmente *Fusarium*, representa un problema para la industria de la cerveza [2, 3]. El desarrollo de los mohos es posible durante algunas de las etapas (remojado y germinación) que constituyen el proceso de malteado debido al aumento de la actividad de agua en el grano, y las consecuencias negativas de su desarrollo afectan tanto al proceso de malteado como a la calidad de la malta, y, por lo tanto, a la calidad de la cerveza. Algunos de los efectos negativos del desarrollo fúngico son: la reducción de la velocidad de germinación de la cebada; el *gushing* (exceso de presión del gas al abrir la cerveza envasada y posterior derrame del líquido), la alteración del color de la cerveza, y la producción de *off-flavors* en la misma [2, 4]. Por otra parte, los mohos pueden producir micotoxinas (metabolitos secundarios tóxicos, como deoxinivalenol, hallado frecuentemente en cerveza [5]), las cuales tienen efectos negativos sobre las levaduras que se emplean en la fermentación, y por lo tanto la eficiencia en esa etapa puede disminuir [2]. Teniendo en cuenta que la contaminación por micotoxinas puede ocurrir también durante el cultivo de la cebada [6, 7], y que durante el malteado no se reduce en forma importante el contenido de las mismas [3, 5], su presencia en el producto final afecta la inocuidad de la cerveza.

En las últimas décadas han surgido agentes físicos y químicos de destrucción microbiana (comúnmente denominados “factores emergentes de conservación”) alternativos a los tratamientos tradicionales para incrementar la inocuidad de alimentos manteniendo su calidad sensorial, nutricional y/o funcional, tanto en productos de consumo directo como en materias primas y productos intermediarios antes de su industrialización. Entre ellos pueden mencionarse altas presiones hidrostáticas, pulsos eléctricos de alto voltaje, ozono, ultrasonido, radiación ultravioleta y luz pulsada [8].

El ozono es un oxidante potente que se utiliza para la purificación de agua y el tratamiento de efluentes [9], y ha sido aprobado como GRAS (Generally Recognized as

Safe) en USA para su uso en el procesamiento de alimentos [10]. Debido a su corta vida útil (se descompone espontáneamente en oxígeno), no queda ozono residual en el producto [11]. El ozono puede ser utilizado para la inactivación de varios microorganismos y la degradación de sustancias químicas en alimentos, en fase líquida o en fase gaseosa [12–14]. En el caso de los cereales, ha sido utilizado en fase gaseosa para la reducción de la carga microbiana, la desinsectación y la inactivación de micotoxinas [15–19]. Por otra parte, al ser burbujeado en agua, el ozono se disuelve parcialmente, formando radicales hidroxilo que pueden oxidar contaminantes con mayor eficiencia que el ozono molecular [14]. La etapa de remojo en el proceso de malteado proporciona condiciones favorables para el tratamiento de los granos de cebada con ozono en fase acuosa, con la finalidad de la inactivación microbiana, dado que la matriz a tratar se encuentra sumergida en agua. Así, el objetivo de este trabajo fue evaluar el efecto de la aplicación de diferentes dosis de ozono en fase acuosa sobre la inactivación fúngica en cebada cervecera contaminada artificialmente con *Fusarium graminearum*, utilizando una columna de burbujeo a escala de laboratorio.

2 Materiales y Métodos

2.1 Muestras

Se utilizó cebada (*Hordeum vulgare* L) de la variedad comercial Andreia, de calidad cervecera. Se desinfectó la cebada sumergiéndola en una solución de NaClO al 5% (v/v) y agitando la mezcla durante 1 min. Se enjuagó la muestra dos veces con abundante agua estéril, agitando cada vez la mezcla por 1 min. Finalmente, se secó la muestra exponiéndola a flujo laminar de aire, en cabina, durante 15 min. La cantidad de cebada utilizada en cada tratamiento fue de 50 g, cantidad que se pesó en recipientes individuales para su posterior inoculación.

2.2 Cepa fúngica e inoculación de las muestras

Se utilizó la cepa 257 del moho *Fusarium graminearum*, productora de deoxinivalenol y zearalenona [20]. Esta cepa pertenece a la colección del laboratorio MICA (Departamento de Industrias de la Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires). El moho se cultivó en medio sólido favorable para la producción de conidios (1 g KH_2PO_4, 1 g KNO_3, 0.5 g KCl, 0.5 g $MgSO_4 \cdot 7H_2O$, 0.2 g glucosa, 0.2 g sacarosa, 20 g agar agar, 20 g cebada molida, 1 L H_2O), y fue incubado a 25 ± 1 °C durante 21 días. Para obtener una suspensión de conidios con la cual inocular las muestras, se agregó agua sobre el cultivo y se removió suavemente con espátula de Drigalsky. El líquido remanente fue filtrado a través de gasa y recolectado en un recipiente estéril. La concentración de conidios de la suspensión se determinó utilizando una cámara de Neubauer (Marienfeld, Alemania), y fue ajustada a 10^6 conidios/mL.

Cada muestra de cebada (50 g) fue inoculada con 10 mL de la suspensión de conidios. Las muestras inoculadas se homogeneizaron mediante agitación manual y se almacenaron a 8 °C hasta el día siguiente, cuando se realizaron los tratamientos. La contaminación de las muestras de cebada inoculada se determinó mediante la técnica de

recuento en placa (Agar Extracto de Levadura, Dextrosa y Cloranfenicol; Biokar Diagnostics, Francia), y fue del orden de 10^4 UFC/g.

2.3 Sistema de ozonización y tratamientos

Se utilizó un equipo generador de ozono por descarga en corona UTK-O-4 (Unitek, Argentina) conectado a una columna de burbujeo de 2 L de capacidad. El ozono fue generado a partir de oxígeno seco de elevada pureza, a un caudal de 5 L/min, y una concentración de 19.58 ± 1.44 mg ozono/L. En este sistema de tratamiento, el gas proveniente del generador ingresa por la parte inferior de la columna de burbujeo, y es dispersado en el líquido a través de un difusor ubicado en la sección posterior a la entrada del gas. Luego de atravesar la columna de burbujeo, y antes de ser liberado al ambiente, el gas es inactivado al entrar en contacto con una solución de KI al 2% (p/v). Este sistema se encuentra instalado dentro de una campana de extracción de gases. Los tratamientos de ozonización se realizaron colocando en la columna de burbujeo la muestra inoculada y 500 mL de agua, y burbujeando el gas en una o en tres etapas según lo descripto a continuación:

Tratamientos en una etapa. La duración de estos tratamientos fue de 5, 15, 30, 45 o 60 min.

Tratamientos en tres etapas. Se realizaron tratamientos de más de una etapa teniendo en cuenta que en el proceso industrial de malteado de la cebada, la etapa de remojo involucra más de un paso de inmersión de los granos en agua. El tiempo de ozonización en cada etapa se eligió en función de los resultados de los tratamientos en una etapa, y fue de 45 min. Una vez finalizada cada etapa, la muestra fue retirada de la columna, el agua fue descartada, se tomó una pequeña cantidad de cebada para llevar a cabo los análisis correspondientes y, posteriormente, se colocó la muestra en la columna junto con otros 500 mL de agua para iniciar la siguiente etapa.

Control. Se denominó de esta manera a las muestras inoculadas que no fueron sometidas a ningún tratamiento.

Controles de lavado. Se llevaron a cabo burbujeando sólo oxígeno (con el generador de ozono apagado), de la misma manera en que se realizaron los tratamientos de ozonización en una o en tres etapas.

Las experiencias se llevaron a cabo a 20 ± 1 °C, y se realizaron tres réplicas por tipo de tratamiento, cada una de ellas en diferentes días, con sus respectivos controles. Las réplicas de los tratamientos en una etapa se llevaron a cabo en días distintos, realizando o bien tratamientos de ozonización, o bien controles de lavado por día. En el caso de los tratamientos en tres etapas, en cambio, fue posible realizar una réplica de ozonización y una de control de lavado en el mismo día.

2.4 Determinación del porcentaje de granos infectados

Se colocaron 10 granos de cebada de cada muestra control o tratada sobre placas de Petri de 90 mm de diámetro con el medio de cultivo Agar Extracto de Levadura, Dextrosa y Cloranfenicol (Biokar Diagnostics, Francia). Las muestras fueron incubadas por separado a tres temperaturas (15, 20 y 25 ± 1 °C), y el recuento de granos infectados se realizó cada 24 h y como máximo hasta 72 h después del inicio de la incubación, o hasta que se hubo observado el 100% de infección en los granos (lo que ocurriera primero). Se contó como positivo el desarrollo de micelio en cada grano a la inspección visual, y se lo expresó como porcentaje de granos infectados (% GI). Las temperaturas de incubación fueron seleccionadas teniendo en cuenta la temperatura óptima de desarrollo del moho (25 °C) y dos temperaturas en las que se lleva a cabo industrialmente el remojo de la cebada (15 y 20 °C). Cada determinación se realizó por triplicado y los resultados se expresaron como el promedio de las réplicas (%) ± desviación estándar.

2.5 Análisis estadístico

Se evaluó la normalidad de las distribuciones de los resultados por tratamiento mediante el test de Shapiro-Wilk ($\alpha = 0.05$). Los resultados del test indicaron que no todas ellas pertenecían a una distribución normal. Por ello, se utilizaron tests no paramétricos de Kruskal-Wallis y de múltiples rangos para evaluar las diferencias entre tratamientos ($\alpha = 0.05$).

3 Resultados y Discusión

3.1 Tratamientos en una etapa

En el primer día de incubación a 20 y 25 °C, el porcentaje de granos infectados (%GI) fue del 100% cuando las muestras fueron tratadas con ozono durante 5 y 15 min, y para todos los controles de lavado. A partir de los 30 min de tratamiento, el %GI de las muestras ozonizadas fue menor (entre 80 y 90%) que el observado para los correspondientes controles de lavado, aunque no significativamente diferente (Fig. 1). En estudios complementarios se observó que el contenido de humedad (en base seca) de los granos llegó al 44,2 y 45,3% a los 30 min de exposición al oxígeno y ozono, respectivamente, hasta un 47,8 y 47,0% a los 60 min. Cuando la temperatura de incubación fue de 15 °C, el %GI de todas las muestras fue inferior al 100%, incluidos los controles. La incidencia de la infección por *F. graminearum* en granos control fue significativamente diferente y superior a la observada en todos los granos ozonizados ($P < 0,0001$), y a la observada a partir de 15 min en el caso de los controles de lavado ($P = 0,0060$). Este es un resultado esperable, puesto que tanto los controles de lavado como las muestras tratadas fueron sometidos a agitación mecánica.

Puede observarse en la Fig. 1 que los %GI de las muestras ozonizadas y sus controles (también en el primer día de incubación a 15 °C) fueron superiores a los correspondientes a los controles de lavado: la causa de estas diferencias pudo deberse a que los ensayos en una etapa se llevaron a cabo en diferentes días, como se indicó en la sección de

Materiales y Métodos, y por lo tanto se partió de un inóculo diferente cada día. Si bien la concentración de conidios de las suspensiones utilizadas para inocular las muestras fue la misma en todas las réplicas, las diferencias en los %GI de los controles pudieron estar relacionadas con la heterogeneidad de la superficie de los granos de cebada, y por ello la forma en que los conidios fueron retenidos en los granos.

El recuento de granos infectados al segundo día de incubación fue del 100% para todos los tratamientos de ozonización y controles de lavado, a las tres temperaturas de incubación. Por lo tanto, si bien se observó un retraso en el desarrollo fúngico en las muestras tratadas al primer día de incubación, al día 2 la incidencia del moho no fue afectada por los tratamientos.

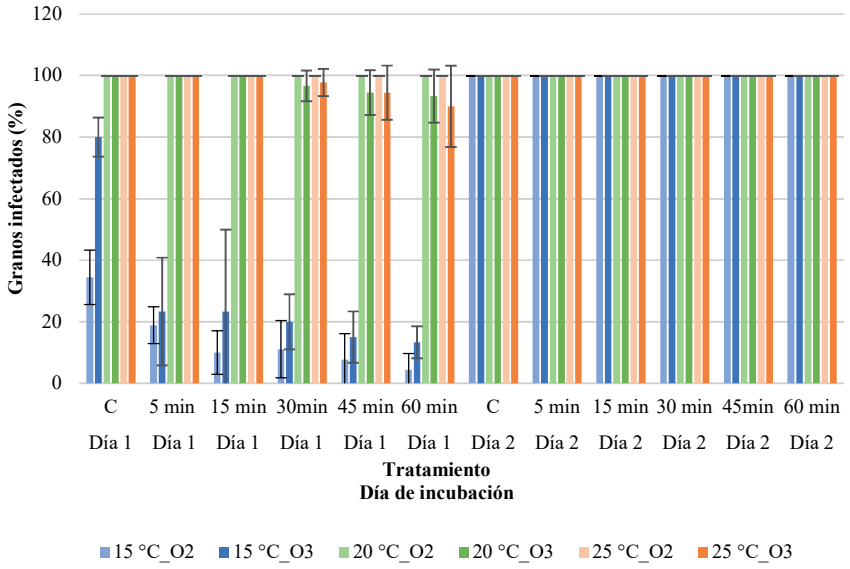

Fig. 1. Porcentaje de granos infectados en control (C), controles de lavado (O_2) y en muestras tratadas con ozono (O_3) durante diferentes períodos de tiempo (5, 15, 30, 45 y 60 min) e incubados a diferentes temperaturas (15, 20 y 25 °C). Las barras corresponden a los valores promedio de las determinaciones, y las barras de error corresponden a ± la desviación estándar.

3.2 Tratamientos en tres etapas

Para la selección del tiempo de ozonización en los tratamientos en etapas, se tuvieron en cuenta los resultados de %GI del primer día de incubación a 20 y 25 °C. Dado que hubo una reducción del %GI respecto de los controles de lavado a 30, 45 y 60 min, se evaluaron las diferencias entre estos tratamientos para cada temperatura. Éstas resultaron no significativas en ambos casos (P = 0,7173 y P = 0,476 para 20 y 25 °C, respec-

tivamente). Sin embargo, el mínimo en el rango de los valores de %GI para los tratamientos de 30 min fue de 90% mientras que para los tratamientos de 45 y 60 min, el mínimo fue de 80%, para ambas temperaturas de incubación. Por lo tanto, se seleccionó entre estos dos últimos, el tratamiento de menor duración (45 min). Los promedios del %GI a 20 °C para 30, 45 y 60 min fueron 96,7 ± 5,0; 94,4 ± 7,3 y 93,3 ± 8,7, respectivamente; y a 25 °C fueron 97,8 ± 4,4; 94,4 ± 7,8 y 93,8 ± 7,4, respectivamente.

De manera similar a lo observado en los tratamientos en una etapa, el %GI fue menor cuanto más baja fue la temperatura de incubación de los granos (Fig. 2). A las 72 h de incubación, no se observaron desarrollos fúngicos adicionales a los observados al segundo día, por lo que la Fig. 2 muestra solo los resultados hasta el día 2. Al segundo día de incubación, el %GI fue del 100% para las muestras de la primera etapa, mientras que, para las muestras ozonizadas de la segunda etapa, los %GI variaron entre 50 y 90%, y entre 45 y 80% para las muestras de la tercera etapa, a las diferentes temperaturas de almacenamiento. En cuanto a los controles de lavado, también se observó una disminución en el %GI a partir de la segunda etapa, aunque los valores de %GI fueron mayores que los observados en las muestras ozonizadas.

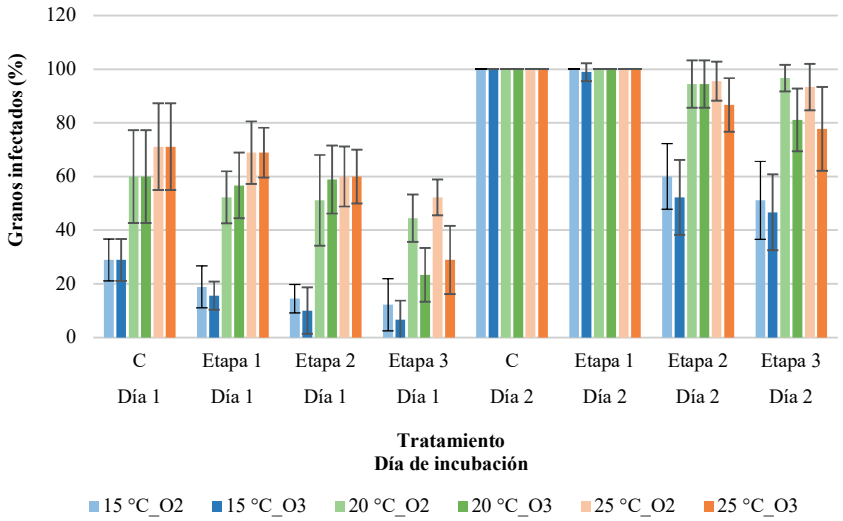

Fig. 2. Porcentaje de granos infectados en control (C), controles de lavado (O_2) y muestras tratadas con ozono (O_3) en etapas (1, 2 y 3) e incubados a diferentes temperaturas (15, 20 y 25 °C). Las barras corresponden a los valores promedio de las determinaciones, y las barras de error corresponden a ± la desviación estándar.

Las tablas 1 y 2 indican la significancia de las diferencias entre el control y las muestras ozonizadas o entre el control y los controles de lavado en las distintas etapas, respectivamente; mientras que la tabla 3 indica la significancia de las diferencias entre el control, las muestras ozonizadas y los controles de lavado en cada etapa. Tanto en el

primer día de incubación como en el segundo, y para las tres temperaturas, no se observaron diferencias significativas entre los %GI del control y la primera etapa de tratamiento, para muestras ozonizadas como para controles de lavado (Tablas 1 y 2). Las muestras ozonizadas en tres etapas presentaron %GI significativamente diferentes a la mayoría de las tratadas en menor número de etapas, según lo observado a ambos días y para algunas temperaturas de incubación (Tabla 1). Este resultado no se repitió en el caso de los controles de lavado, donde sólo se observaron diferencias significativas a 25 °C el primer día de incubación, y a 15 y 25 °C el segundo día (Tabla 2).

En cuanto a las diferencias entre muestras ozonizadas y controles de lavado en la misma etapa, para las observaciones de %GI en ambos días de incubación, a las temperaturas de 15 y 20 °C no hubo diferencias significativas entre los %GI de las muestras ozonizadas y de los controles de lavado. A 25 °C, los valores correspondientes a las muestras ozonizadas en la segunda y tercera etapa fueron significativamente diferentes ($P < 0,05$) y menores, que los %GI de los controles de lavado (Tabla 3).

La ozonización en tres etapas de cebada inoculada con *F. graminearum* permitió reducir la contaminación inicial del moho, a pesar de no haberse alcanzado la completa inactivación del mismo. Si bien se observó un efecto del lavado, el ozono fue más efectivo para lograr la reducción de la contaminación fúngica, sobre todo a las mayores temperaturas.

Tabla 1. Diferencias significativas ($P < 0,05$) entre control (C) y etapas (1, 2 y 3) de tratamientos de ozonización al primer y segundo día de incubación de las muestras a diferentes temperaturas (15, 20 y 25 °C). Los grupos homogéneos se encuentran alineados en la misma columna.

	Control *vs* muestras ozonizadas							
Día de incubación	Etapas/T (°C)	15		20		25		
1	C	X		X		X		
	1	X		X		X		
	2	X	X	X		X		
	3		X		X			X
2	C	X		X		X		
	1	X		X		X		
	2		X	X				X
	3		X		X			X

Tabla 2. Diferencias significativas (P < 0,05) entre control (C) y etapas (1, 2 y 3) de controles de lavado al primer y segundo día de incubación de las muestras a diferentes temperaturas (15, 20 y 25 °C). Los grupos homogéneos se encuentran alineados en la misma columna.

	Control *vs* controles de lavado					
Día de incubación	Etapas/T (°C)	15		20	25	
1	C	X		X	X	
	1	X		X	X	
	2	X		X	X	X
	3	X		X		X
2	C	X		X	X	
	1	X		X	X	
	2		X	X	X	X
	3		X	X		X

Tabla 3. Diferencias significativas (P < 0,05) entre tratamientos de ozonización y controles de lavado en las diferentes etapas (1, 2 y 3) al primer y segundo día de incubación de las muestras a diferentes temperaturas (15, 20 y 25 °C). Los grupos homogéneos se encuentran alineados en la misma columna.

	Muestras ozonizadas *vs* controles de lavado					
Día de incubación	Etapas/T (°C)	15		20	25	
1	C	X		X	X	
	1	X		X	X	
	2	X		X	X	
	3	X		X		X
2	C	X		X	X	
	1	X		X	X	
	2	X		X		X
	3	X		X		X

4 Conclusiones

El estudio de la ozonización en una etapa a diferentes dosis de tratamiento permitió la selección de la dosis de ozonización para los tratamientos multietapa, que se asimilan a los diferentes pasos de la etapa de remojo de la cebada cervecera en el proceso industrial de malteado. El tratamiento con ozono en 3 etapas redujo significativamente la contaminación de *F. graminearum* durante 72 h, evidenciándose el efecto positivo de la ozonización con respecto a sólo el proceso de lavado cuando la incubación se realizó a 20 y 25 °C. A 15 °C no hubo un efecto adicional significativo del ozono sobre el efecto mecánico del lavado. Así el ozono es una alternativa ambientalmente amigable de interés para reducir la contaminación fúngica de la cebada durante el malteado cuando el mismo se realiza a temperaturas en el rango óptimo de desarrollo del moho.

Están en curso investigaciones acerca del efecto de los tratamientos de ozonización en 3 etapas sobre la capacidad germinativa de la cebada, parámetro fundamental para el proceso de malteado. Estudios preliminares han mostrado que la misma no se altera en tratamientos de hasta 60 min en condiciones operativas similares.

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Valorización de residuos provenientes del salado-madurado de anchoíta (*Engraulis anchoita*)

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Resumen. El proceso de salado-madurado de anchoíta (*Engraulis anchoíta*) genera en nuestro país un gran volumen de residuos, que no pueden ser destinados a la obtención de harina y aceite de pescado por su alto tenor salino. En este trabajo se busca caracterizar este residuo y evaluar la posibilidad de aplicar un proceso de desalado que permita su posterior reprocesamiento. Se aplicó un proceso de desalado con agua corriente en tres etapas, evaluándose el efecto sobre la retención de macronutrientes. Se determinó que los residuos contienen un 17,6% NaCl, con un 14,8% proteína y 3,5% de lípidos, de los cuales el 20,3% corresponden a ácidos grasos poliinsaturados, representados principalmente por EPA y DHA. El desalado propuesto permitió reducir el contenido de NaCl hasta 1,6%, sólo con 1,3% y 0,35% de pérdida de proteína y lípidos hacia la solución, respectivamente. Los residuos de anchoíta salada-madurada sometidos a un proceso sencillo de desalado, presentaron componentes con alto valor biológico, que los hace interesantes para reintegrar a distintos ciclos productivos.

Palabras Clave: Subproductos de la pesca, Desalado, Propiedades Fisicoquímicas, Ácidos grasos poliinsaturados.

1 Introducción

El pescado es una de las fuentes más importantes de nutrientes como proteínas, vitaminas y minerales, considerándose la mayor reserva de ácidos grasos poliinsaturados, especialmente omega-3 [1]. Los residuos generados por su procesamiento pueden representar entre 30 y 70%, con un volumen en aumento debido a la demanda creciente de los consumidores [2]. Particularmente, la anchoíta (*Engraulis anchoita*) constituye uno de los principales recursos pesqueros de nuestro país, destinado principalmente a la producción de anchoíta salada-madurada. Esta industria genera alrededor de 7.000 ton/año de residuos, que no pueden aprovecharse en la producción de harina o aceite de pescado debido a su alto contenido de sal (NaCl), que puede alcanzar 55 % dependiendo de las particularidades del proceso. Por este motivo, estos residuos son desechados al predio de disposición final, con el consecuente impacto ambiental asociado. Para

su reintegración a los ciclos productivos es necesario previamente realizar un tratamiento que reduzca el contenido de sal a niveles compatibles con los distintos procesos.

En este contexto, se propone el estudio del desalado de residuos de la elaboración de anchoíta salada-madurada y su efecto sobre la retención de macronutrientes, aportando de esta forma estrategias que favorezcan el agregado de valor y el uso integral de los recursos pesqueros comerciales.

2 Metodología

2.1 Procedimiento de desalado

Se utilizaron residuos del proceso industrial de salado-madurado de *E. anchoíta* (Mar del Plata, Argentina), constituidos principalmente por cabezas y parte de las vísceras. El desalado consistió en la inmersión en agua corriente (16 ± 2 °C) durante un tiempo total de 5 horas, con dos renovaciones de agua a 1,75 y 3,75 h y una relación solución-residuo 2:1. Se extrajeron muestras (20 g) a distintos tiempos de desalado, se homogeneizaron y almacenaron a 5 ± 1 °C para su análisis.

2.2 Análisis fisicoquímicos

La composición química proximal de los residuos fue determinada según AOAC [3] y el contenido de NaCl mediante el método de Mohr [4]. En el agua de desalado se determinó proteína soluble por Lowry et al. [5] y contenido de lípidos como sustancias solubles en éter etílico. El perfil de ácidos grasos (AG) se determinó por cromatografía gaseosa (Shimadzu GC-17^{A}, Japón). Los análisis se realizaron por triplicado.

Los cambios en el contenido de macronutrientes durante el tratamiento se evaluaron a partir de ANOVA y test de Tukey para comparación de medias (R Development Core Team, Version 4.2 2020), $p<0.05$.

3 Resultados y discusión

3.1 Caracterización de los residuos

La composición de los residuos sin tratar fue: 62,5 ± 0,5% de agua, 23,1 ± 0,2% de cenizas, 14,8 ± 0,5% de proteínas y 3,5 ± 0,2% de lípidos con un tenor salino de 17,6 ± 0,2%. Los datos disponibles en bibliografía se refieren en general a la porción comestible, habiéndose reportado en músculo de anchoíta salada un contenido de agua en el rango 55-60 g/100g y un contenido de NaCl entre 17 y 47 g/100g [6]. Los residuos presentan una CQP diferente debido a la gran proporción de cabezas, piel, vísceras y escamas. En cuanto a la composición de AG (**Tabla 1**), se determinó en los residuos una predominancia de ácidos grasos saturados (AGS), mayormente representados por el palmítico (16:0) (0,233 ± 0,003 g/g_{grasa}); seguido por los monoinsaturados (AGMI), siendo el oleico (18:1 n9) el de mayor proporción (0,101 ± 0,000 g/g_{grasa}). Los ácidos grasos poliinsaturados (AGPI) representaron el 20,3%, con los porcentajes más altos

para la familia omega-3 (EPA y DHA). Esto se contrapone con los datos disponibles para productos de anchoíta, que presentan una prevalencia de AGMI y AGPI con menor proporción de AGS [6]. De acuerdo a estos resultados, resulta evidente el efecto del salado sobre la fracción AGPI, explicado por su alta sensibilidad a la oxidación combinada con la presencia de factores pro-oxidantes durante el proceso, como enzimas y restos de sangre.

3.2 Proceso de desalado

El proceso de desalado permitió reducir el contenido de NaCl en los residuos, alcanzando valores finales de 1,6% con un contenido de humedad de 75,1% (**Figura 1**). Se observa que las mayores modificaciones se produjeron durante la primera etapa (1,75h), disminuyendo el contenido de NaCl un 70% con respecto al valor inicial.

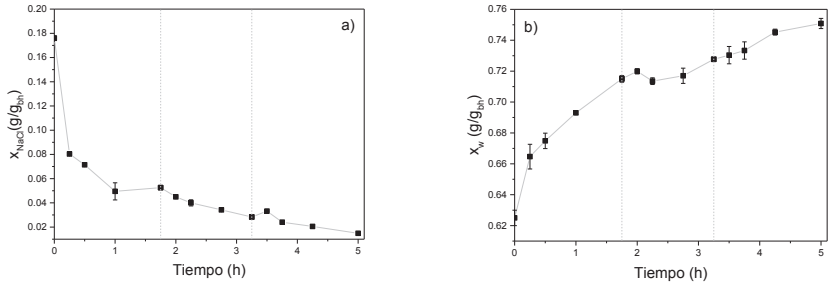

Fig. 1. Evolución del contenido de NaCl (a) y del contenido de agua (b) durante el desalado de residuos del salado-madurado de anchoíta.

Tabla 1. Contenido de proteínas, lípidos (g/g) y perfil de ácidos grasos (g/g de grasa) en el residuo y solución de desalado durante el proceso.

	Tiempo de desalado			
	0 h	1,75 h (Etapa 1)	3,75 h (Etapa 2)	5 h (Etapa 3)
RESIDUO				
Proteínas	0,148 ± 0,005 [a]	0,128 ± 0,006 [a]	0,148 ± 0,005 [a]	0,142 ± 0,014 [a]
Lípidos	0,035 ± 0,002 [a]	0,038 ± 0,003 [a]	0,051 ± 0,003 [b]	0,047 ± 0,001 [c]
AGS	0,486 ± 0,007 [a]	0,424 ± 0,015 [b]	0,518 ± 0,008 [a]	0,437 ± 0,019 [b]
AGMI	0,231 ± 0,002[a]	0,324 ± 0,021[b]	0,228 ± 0,012[a]	0,280 ± 0,011[c]
AGPI	0,203 ± 0,003[a]	0,193 ± 0,005[a]	0,201 ± 0,007[a]	0,209 ± 0,009[a]
EPA+DHA	0,141 ± 0,002	0,156 ± 0,003	0,161 ± 0,005	0,158 ± 0,005
SOLUCIÓN DE DESALADO				
Proteínas	-	0,0089 ± 0,0005[a]	0,0027 ± 0,0004[b]	0,0014 ± 0,0002[c]
Lípidos	-	0,0022 ± 0,0005[a]	0,0005 ± 0,0000[b]	0,0008 ± 0,0001[b]
AGS	-	0,225± 0,019[a]	0,367 ± 0,018[b]	0,320 ± 0,034[b]
AGMI	-	0,136 ± 0,013[a]	0,199 ± 0,028[a]	0,176 ± 0,029[a]
AGPI	-	0,308 ± 0,016[a]	0,211 ± 0,022[b]	0,183 ± 0,015[b]
EPA+DHA	-	0,070 ± 0,003	0,090 ± 0,007	0,026 ± 0,007

Letras diferentes en una misma fila indican diferencias significativas ($p<0,05$).

De acuerdo a la **Tabla 1**, las mayores pérdidas hacia la solución de desalado ocurrieron durante la primera etapa. Luego de 5 h, sólo el 1,3% y 0,35% de proteínas y lípidos, respectivamente, se perdieron en el agua de desalado (porcentaje acumulado). En la etapa 1, se determinó un mayor aporte de AGPI en la disolución, sugiriendo una hidrólisis preferencial de esta fracción, que se encuentra en estado líquido a temperatura ambiente, favoreciendo la acción de las lipasas [7]. En forma global, el tratamiento no llevó a una pérdida significativa de proteínas desde los residuos hacia el agua de desalado, así como tampoco a una modificación en la proporción de los distintos grupos de AG.

4 Conclusiones

Los residuos del salado-madurado de anchoíta presentaron un contenido considerable de biomoléculas de alto valor biológico, como proteínas y lípidos, reforzando la idea de la importancia de su recuperación como subproducto y del diseño de tratamientos adecuados que permitan su reincorporación a los ciclos productivos, como la obtención de harina de pescado u otros productos con valor agregado tales como hidrolizados proteicos y obtención de extractos ricos en ácidos grasos omega-3. El desalado propuesto podría servir de base para el diseño de procesos, considerando la reducción del contenido de NaCl alcanzada y la alta retención de macronutrientes.

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Arsénico en agua y alimentos: determinación del perfil de riesgo en Argentina

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Abstract. El Arsénico (As) es un elemento que se encuentra ampliamente distribuido en la naturaleza. Los compuestos de As inorgánico (iAs) son los más tóxicos y, clasificados como agentes cancerígenos, ocasionan múltiples efectos negativos sobre la salud. La exposición humana al As se da principalmente por la ingesta de agua y alimentos. Argentina presenta vastas zonas con aguas con altas concentraciones de As, superiores al límite recomendado de 0,01 mg/L. En alimentos, pescados y mariscos, arroz y algas marinas tienen naturalmente los niveles más altos de As. En este trabajo se realizó el Perfil de Riesgo de As en agua y alimentos, mediante la revisión sistemática de más de 100 documentos científicos y normativa relacionada, encontrándose que la ingesta de As en Argentina podría suscitar una preocupación de Salud Pública. Es de crucial importancia el conocimiento certero de los riesgos asociados a la baja exposición al As, el contenido de iAs en diferentes matrices alimenticias y el efecto del procesamiento tecnológico y culinario sobre la especiación y concentración, que permitan la elaboración de informes fehacientes y con visión a futuro sobre el estado de contaminación.

Keywords: Análisis de Riesgo, Peligro Químico, Agua, Alimentos, Inocuidad.

1 Introducción

El arsénico (As) se encuentra naturalmente en las aguas subterráneas y las actividades antropogénicas contribuyen a su incremento, por lo que existen valores superiores al límite (0,01 mg/L) en aguas de bebida. El As ingresa al organismo por consumo de estas aguas, de cultivos regados con agua contaminada y de organismos filtradores o sus predadores. Las formas inorgánicas (III) y (V) son las más tóxicas, clasificadas como agentes carcinógenos [1], [2]. En Argentina existen vastas zonas con agua con niveles de As perjudiciales para la salud. Si bien en el siglo XX se confirmó que la exposición a las mismas daba lugar al Hidroarsenicismo Crónico Regional Endémico (HACRE), aún existe incertidumbre sobre la magnitud de la población expuesta, siendo necesario un programa permanente de vigilancia de los niveles de As en recursos hídricos.

El Perfil de Riesgo es una etapa preliminar del Análisis y la Gestión de Riesgos para la inocuidad de los alimentos, siendo la base para iniciar una evaluación de riesgo. Provee información relevante acerca de la combinación peligro/alimento, la caracterización del peligro y el riesgo existente en la cadena alimentaria [3]. El objetivo fue describir mediante el Perfil de Riesgo el problema de inocuidad de alimentos y del agua con altas concentraciones de As, a fin de identificar los elementos de relevancia para la gestión de riesgos.

2 Metodología

Se realizó un Perfil de Riesgo del peligro químico Arsénico, en agua y en alimentos de acuerdo a los lineamientos de FAO [3]. Para ello se describió la combinación peligro/alimento, se identificó y caracterizó el peligro y se analizó la exposición del ser humano al mismo a través de la ingesta, los posibles riesgos asociados a la misma y sus consecuencias para la salud, mediante la recopilación y revisión sistemática de más de 100 fuentes de documentos científicos y normativa relacionada.

3 Resultados y Discusión

3.1 Identificación del peligro: Arsénico

La toxicidad del As varía según su forma arsenical, valencia, solubilidad, estado físico, pureza y tasas de absorción y eliminación. Los arsenitos y arseniatos son formas de iAs altamente solubles en agua, generalmente más tóxicas que el As orgánico que se elimina rápidamente del organismo. Los compuestos arsenicales de mayor a menor toxicidad son: inorgánicos trivalentes > orgánicos trivalentes > inorgánicos pentavalentes > orgánicos pentavalentes > As elemental [4].

En la naturaleza, el As cuenta con ciclos asociados a actividades geológicas y antropogénicas, entre estas últimas, pigmentos, componentes electrónicos, aleaciones de cobre o plomo, minería, plaguicidas, herbicidas, fertilizantes. La presencia natural se asocia a la corteza terrestre, suelos, sedimentos, aire, agua, organismos vivos, polvo volcánico y continental y quema de vegetación [4]. Las actividades humanas y eventos naturales transfieren As al ambiente, de éste a la atmosfera, precipitando con el agua de lluvia y llegando a la superficie continental, sedimentos oceánicos y agua; y en general a través del agua a los alimentos [4], [5].

3.2 Normativa nacional

De acuerdo con las recomendaciones de la OMS, en 2019 la normativa argentina estableció un valor máximo de 0,01 mg/L de As en agua potable de suministro público y uso domiciliario, en aguas de bebida o potabilizadas envasadas y en aguas mineralizadas [6]. Sin embargo, en agua mineral natural y sus productos, se admite un valor muy superior (0,2 mg As/L). En alimentos se establecen límites máximos de contaminantes inorgánicos en un rango de 0,01-1 mg/kg (Art. 56) [6].

3.3 Caracterización del peligro

La vía de ingreso más importante del As es por la ingesta, acumulándose en hígado, bazo, riñones, pulmones y tracto gastrointestinal. Los efectos en la salud dependen de la dosis y duración de la exposición[4]. Semanas o meses de exposición a altas dosis de As (0,04 mg/kg/día) resulta en efectos inespecíficos reversibles. Cuando se trata de exposición crónica, la variedad de problemas en la salud se conoce en Argentina como HACRE. Se caracteriza por efectos dérmicos, como hiperpigmentación luego de 5-15 años de ingestión de bajas dosis (≥ 0,01 mg/kg/día) o 6 meses a 3 años de altas dosis (0,04 mg/kg/día). Además, se asocia a enfermedad vascular, diabetes, hipertensión y efectos sobre los sistemas inmune y respiratorio. El As ha sido clasificado como cancerígeno (grupo I) por el IARC y como cancerígeno (grupo A) por la USEPA [1].

3.4 Exposición al peligro: Arsénico/agua

Investigaciones en Argentina demostraron la existencia de una gran área con aguas con más de 0,05 mg As/L, la cual se extiende en un continuo noroeste-sureste desde el Altiplano hacia la Costa Atlántica, subdividiéndose en zona cordillerana, pericordillerana y pampeana. El origen del As es principalmente natural, debido a la actividad volcánica e hidrotermal de la cordillera de los Andes [1]. Las provincias más afectadas son Córdoba, Santiago del Estero, Chaco, Salta, Tucumán, Santa Fé y La Pampa. Actualmente, la cifra de argentinos que vive en áreas contaminadas (>0,05 mg As/L) asciende a cuatro millones [7], [8].

3.5 Exposición al peligro: Arsénico/alimentos

En general, la proporción de iAs en alimentos comprende el 50-100% del As total [5]. El iAs predomina en carnes, lácteos y cereales, pero también está presente en vegetales y frutas [9]. El contenido de As en alimentos de origen terrestre es generalmente bajo, por lo que la cantidad de iAs es también baja. Excepción es el arroz con importante contenido de iAs [5]. Por otro lado, los pescados y mariscos pueden tener elevado contenido de As pero proporción relativa de iAs usualmente muy baja [10]. De arroz y pescados se han reportado exceso de los limites nacionales permitidos. Los vegetales contienen en su mayoría (>40 %) iAs [11]. La principal fuente de iAs para los argentinos, considerando la ingesta y el porcentaje de iAs respecto del total, correspondería a harina de trigo y derivados y luego el arroz, cuyo consumo es bajo, pero la cantidad de iAs en el mismo es elevada. La contribución de la carne de res resultaría importante debido a su alto consumo [5].

4 Conclusiones

La exposición al As a través del agua y alimentos en Argentina podría suscitar una preocupación de Salud Pública, principalmente debido a la existencia de zonas con

contenidos de As en agua mayores al límite establecido. Pescados y mariscos, carnes y arroz presentan valores más elevados, por lo que la cuantificación de As total, iAs y As orgánico debe ser más exhaustiva en los mismos. Es necesario el continuo relevamiento de las regiones con HACRE y con fuentes de agua contaminadas, ya que la información disponible actualmente no posibilita una evaluación del riesgo completa. Se debe continuar trabajando para que los organismos pertinentes puedan elaborar informes fehacientes y con visión a futuro sobre el estado de contaminación con As en Argentina de forma de poder tomar medidas preventivas y decisiones de mejora.

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Microbioma de *Engraulis anchoíta* salada-madurada

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Abstract. El proceso de salado-madurado permite el desarrollo de una gran diversidad de procariotas halófilos. En Latinoamérica este método de preservación se utiliza para la especie *Engraulis anchoita*. En el presente estudio se analiza el microbioma de dos muestras de este producto. Se encontró mayor abundancia de OTUs de bacterias (>97%) con una baja proporción de arqueas. Los OTUs con una abundancia mayor al 5% correspondieron a bacterias de los géneros *Marinobacter* (SA1 17,5% y SA2 14,3%), *Thalassospira* (SA1 15,5% y SA2 17,7%), *Alcanivorax* (SA1 14,5% y SA2 10,7%) y *Parvibaculum* (SA1 6,6% y SA2 12,0%), de las familias *Flavobacteriaceae* (SA1 11,2% y SA2 15,3%) y *Rhodospirillaceae* (SA1 6,3% y SA2 6,1%) y 9,4% y 5,8% de los OTUs de SA1 y SA2, respectivamente, que se pudieron clasificar solo hasta la *clase Gammaproteobacteoria*. Esto indicaría que las bacterias podrían adaptarse mejor como cultivos iniciadores del proceso para mantener las características típicas del producto. Además, se determinó que este producto es fuente de microorganismos novedosos, con el potencial biotecnológico que esto representa.

Keywords: Microbioma, Procariotas halófilos, Anchoíta, Fermentación.

1 Introducción

Diferentes especies pesqueras se pueden conservar mediante salado-madurado, práctica adoptada en América Latina utilizando *Engraulis anchoíta* que alcanza un alto contenido de NaCl (14–20% w/w) y baja actividad de agua (a_w~0.75) [1], lo que contribuye a prevenir el desarrollo de microorganismos patógenos y deteriorantes típicos del pescado fresco. La fermentación de alimentos involucra microorganismos que modifican características sensoriales mediante una diversa gama de actividades enzimáticas. Cuando se realizan en presencia de altos contenidos de sal, resultan en el desarrollo de una gran diversidad de microorganismos autóctonos halófilos o halotolerantes capaces de sobrevivir y crecer en ambientes hipersalinos. Pese a que estos productos se encuentran en constante estudio [2]–[4], el microbioma de la *Engraulis anchoíta* salada-madurada no ha sido analizado hasta el momento. Por lo antedicho, el objetivo del presente

estudio se enfoca en el estudio del microbioma de la anchoíta salada-madurada enfocado a aplicaciones tecnológicas.

2 Metodología

Se colectaron dos muestras (SA1 y SA2) de anchoíta (*Engraulis anchoita*) de diferentes capturas, salada, descabezada y parcialmente eviscerada, de la etapa de maduración en barriles de una planta procesadora en Mar del Plata, Argentina; cuyo proceso de elaboración constó de una etapa de salado-húmedo de los ejemplares enteros seguido de la maduración de troncos de anchoíta acondicionados con sal en barriles [4]. Se homogeneizaron 50 g de muestra en caldo salino estéril (NaCl, 150 g/L; peptona de carne, 3 g/L; extracto de carne, 3 g/L) y se dejó reposar por 30 min [5]. La matriz del alimento se separó por centrifugación a 3.000 g por 5 min. El sobrenadante obtenido se centrifugó a 10.000 g por 10 min y los pellets se resuspendieron en etanol 70% (v/v) y almacenaron a 4°C hasta la extracción de ADN [6]. Para el análisis del microbioma se utilizaron los primers 15F(Parada)-806R(Apprill): FWD:GTGYCAGCMGCCGCGGTAA; REV:GGACTACNVGGGTWTCTAAT enfocado a regiones altamente conservadas en procariotas y a la región hipervariable V4 del 16S rARN. Los resultados se analizaron de acuerdo al paquete QIIME version 1.9.1 [7]. Las secuencias con más de un 97% de similitud fueron agrupadas en unidades taxonómicas operacionales (operational taxonomic units, OTUs). Las secuencias representativas se analizaron con la base de datos SILVA 132 (versión 132, publicada en abril de 2018) utilizando el Naïve Bayesian Classifier [8].

3 Resultados y Discusión

Se determinó la composición de la secuenciación de amplicones Illumina del gen 16S ARNr dirigido a la región hipervariable v4, obteniendo datos de secuencias de 300 pb en promedio con 96664 lecturas para SA1 y 96306 para SA2. El patrón de la composición total se puede observar en la Fig. 1. Se detectaron múltiples OTU que contribuían con al menos un 0,1% a la composición del microbioma del consorcio. En este sentido, hubo 34 OTUs para SA1 y 28 en SA2, sin cambios en las OTU predominantes. La abundancia de las arqueas fue minoritaria, siendo que el 97,8% y 99,5% de las lecturas de SA1 y SA2, respectivamente, correspondieron a eubacterias. Los OTUs con una predominancia mayor al 5% fueron en ambos casos bacterias de los géneros *Marinobacter* (SA1 17,5% y SA2 14,3%), *Thalassospira* (SA1 15,5% y SA2 17,7%), *Alcanivorax* (SA1 14,5% y SA2 10,7%) y *Parvibaculum* (SA1 6,6% y SA2 12,0%), de las familias *Flavobacteriaceae* (SA1 11,2% y SA2 15,3%) y *Rhodospirillaceae* (SA1 6,3% y SA2 6,1%) y 9,4% y 5,8% de los OTUs de SA1 y SA2, respectivamente, que se pudieron clasificar solo hasta la clase *Gammaproteobacteria*. Entre las arqueas, la mayor presencia se dio en SA1 con 2,66% de los OTUs pertenecientes a *Halobacteriaceae*, dentro esta familia encontrando los géneros *Haloquadratum* (0,25%), *Halorhabdus* (0,02%) y *Haloarcula* (0,01%). Muchos miembros de estos géneros y familias se han encontrado halófilos en pescado y ambientes marinos, y algunos de ellos en productos

pesqueros salado-madurados. Cabe destacar que múltiples OTUs no pudieron atribuirse a una taxonomía precisa de género/especie con una secuencia de referencia similar (> 97%) a una cepa tipo, indicando la presencia de especies potencialmente novedosas, como todas las OTU de nueva referencia y las OTU provenientes de cepas donde la taxonomía máxima que infirió solo a nivel familiar.

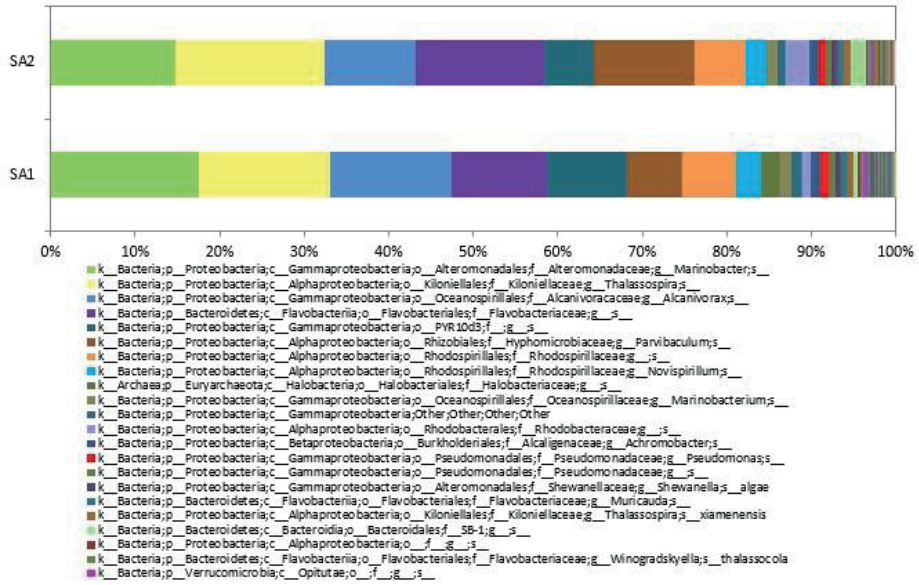

Fig. 1. Composición del microbioma de las muestras de anchoíta salada-madurada.

Dado que el proceso de elaboración de *Engraulis anchoíta* salada-madurada puede proporcionar las condiciones necesarias para la formación de aminas biogénas, para los humanos [1], resulta de interés evaluar la presencia de OTUs próximos a géneros de procariotas degradadores de histamina asociados a previamente a este producto a fin de controlar su presencia. La histamina puede causar una intoxicación alimentaria similar a una alergia, que es la enfermedad transmitida por los alimentos más común relacionada con los productos pesqueros, por lo que su contenido está regulado en estos alimentos [1]. En este sentido, se encontraron cepas pertenecientes a los géneros *Halobacterium*, *Halomonas* y *Halovibrio* capaces de degradar histamina [9]. En las muestras analizadas en el presente estudio, la abundancia de OTUs de *Halomonas* fue 0,09% en SA1 y 0,28% en SA2, mientras que los otros géneros no fueron encontrados.

4 Conclusiones

Se encontró que en este alimento la abundancia predominante corresponde a bacterias con una muy baja incidencia de arqueas. El conocimiento del microbioma puede contribuir a la toma de decisiones para la mejora del proceso de salado-madurado de anchoíta. De particular importancia resultan estos hallazgos para la selección de microorganismos iniciadores de la maduración, indicando que las bacterias podrían adaptarse mejor como cultivos iniciadores del proceso considerando también mantener las características típicas del producto. Además, se determinó que este producto es fuente de microorganismos novedosos, con el potencial biotecnológico que esto representa.

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Efecto del ozono en fase acuosa sobre las ceras epicuticulares y el color de arándanos (*Vaccinium corymbosum* L.,cultivar O'Neal)

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Resumen. El tratamiento con ozono es una alternativa de procesamiento mínimo para aumentar la vida útil de frutas, con reducido impacto en la calidad global. El objetivo de este trabajo fue evaluar los cambios en las propiedades ópticas y en las ceras epicuticulares (CE) de arándanos expuestos a 5,1 $mg.L^{-1}$ de ozono en fase acuosa durante 10 min y almacenados a 4 ± 1 ºC durante 15 días. Se adquirieron espectros de frutos con CE (fruto entero), frutos sin CE y sólo CE tanto de frutos ozonizados como control. Los espectros fueron preprocesados utilizando distintos métodos (primera y segunda derivada y normalización de vectores) para eliminar la variabilidad no deseada, y se utilizó un análisis de componentes principales (PCA) para agrupar las muestras. La primera derivada permitió explicar la variabilidad de las muestras y obtener una buena separación de los diferentes grupos de espectros (frutos con CE, frutos sin CE y sólo CE), además de una buena clasificación de las muestras tratadas con ozono y sin tratar. Los espectros FT-IR revelaron varias señales asignadas a las CE y la cutina. El efecto del ozono en las CE se manifestó con la aparición de nuevas bandas (estiramiento de C=O a 1701 cm^{-1}, debido a la oxidación de alcoholes a carbonilos, o 1542 cm^{-1}), y desplazamiento de otras (1464-1472 a 1468 cm^{-1} para el tijereteo de CH_2 o 730 a 724 cm^{-1} para el balanceo de CH_2). Sin embargo, estos cambios en CE no afectaron significativamente el color de los arándanos ozonizados.

Palabras clave: Arándano, Ozono, Espectros FT-IR

1 Introducción

El cultivo de arándano es relativamente joven en Argentina, siendo su principal ventaja la contra-estacionalidad con el hemisferio norte, lo cual permite que el 95 % del fruto fresco sea exportado a los Estados Unidos. Las principales variedades plantadas en el país son Misty y O'Neal, siendo esta última la predominante en la provincia de Buenos Aires. En la actualidad el Comité Argentino de Arándanos desarrolla estrategias para incrementar el consumo de esta fruta en el mercado local y posicionar el arándano como una alternativa de consumo de fruta fresca y natural, destacando sus beneficios a la salud asociados con su alto contenido de vitamina C y compuestos fenólicos, que califican a esta fruta como un "superalimento". Esta baya es altamente propensa al deterioro postcosecha debido principalmente a cambios fisiológicos, daños físicos y contaminación por bacterias y hongos, pérdida de agua, y ablandamiento, entre otros [1,2].

Varios estudios destacan la importancia de las ceras epicuticulares (CE) en diferentes bayas (arándanos, uvas, ciruelas). Las CE contribuyen a inhibir el ataque fúngico en estos frutos y constituyen una barrera para la pérdida de agua, además de ser consideradas un parámetro de calidad desde el punto de vista comercial: la ausencia de éstas resulta en una apariencia poco atractiva y dan impresión de mala calidad [2-6]. Los frutos de arándano cv. O'Neal tiene un contenido de cera cuticular de alrededor de 100 $\mu g/cm^2$, constituidas principalmente por triterpenoides pentacíclicos (especialmente ácido urólico, ácido oleanólico y lupol) y β-dicetonas (principalmente hentriacontan-10,12-diona), que representan el 64,2 % y 16,4 % del total de las CE, respectivamente [7].

En la actualidad, la creciente demanda por parte de los consumidores de productos naturales o símil frescos ha llevado al estudio y desarrollo de nuevas tecnologías que permitan extender la vida útil de frutos y vegetales, sin ocasionar un impacto negativo en las características organolépticas y nutricionales de los mismos. Entre las principales tecnologías de procesamiento mínimo estudiadas, se encuentra el ozono [8,9] que se caracteriza por su alto poder oxidante y corta vida útil, que se traduce en propiedades bactericidas y viricidas sin dejar residuos en el producto. En el año 2002, la FDA aprobó su uso en el tratamiento postcosecha de frutas y vegetales. Diversos estudios han establecido la efectividad del uso de agua ozonizada para el lavado de frutos finos previamente inoculados con patógenos como *Escherichia coli* O157:H7 y *Salmonella enterica* [10,11]. En estudios previos del grupo se demostró la efectividad de tratamientos de ozono en fase acuosa (3,0 y 5,1 mg $O_3.L^{-1}$) durante 10, 15, 20 y 30 min en la reducción de la micobiota nativa durante el almacenamiento refrigerado. Estos tratamientos no produjeron alteraciones en los parámetros mecánicos de los frutos, pero incrementaron la pérdida de peso en comparación con el fruto sin tratar. En particular, el tratamiento de ozonización que causó la menor pérdida de peso fue 10 min de exposición a 5,1 mg $O_3.L^{-1}$ [12]. En función del rol que cumplen las CE en la pérdida de peso y, ante la escasez de estudios sobre la caracterización de las ceras epicuticulares de frutos de arándano o sus cambios como consecuencia de los tratamientos con ozono, el objetivo del presente trabajo fue evaluar el efecto del tratamiento con ozono en fase acuosa (5,1 mg $O_3.L^{-1}$, 10 min) en la superficie del fruto mediante la

adquisición de espectros FT-IR(con énfasis en las ceras epicuticulares), y mediante la evaluación del color a los 0 y 15 días de almacenamiento a 4 ± 1 ºC.

2 Materiales y métodos

2.1 Materia prima

Se utilizaron frutos orgánicos de *Vaccinium corymbosum* (arándano alto) cultivar O'Neal provenientes de la provincia de Buenos Aires, Argentina. Para evitar la variabilidad debido al estadio de madurez, se trabajó con un lote homogéneo. Para la selección de los frutos se tomó en cuenta el tamaño, la forma, el color y la ausencia de infección microbiológica o daño físico. El tamaño de los frutos fue de 1,8 ± 0,2 cm de diámetro y su peso 2,0 ± 0,2 g. Los frutos fueron mantenidos bajo refrigeración (3 ± 1 ºC) hasta 30 min antes de los tratamientos.

2.2 Tratamiento de ozono en fase acuosa

Las muestras fueron ozonizadas en un equipo provisto de un generador de ozono UTK-O-4 (Unitek S.A., Argentina), una columna de burbujeo con difusor incluido y un tanque de oxígeno. Los frutos fueron ozonizados con una concentración de ozono en la corriente gaseosa de entrada a la columna de burbujeo de 18 ± 2 mg $O_3.L^{-1}$ durante 10 min. El ozono se burbujeó en forma continua en 1500 mL de agua destilada a 20 ± 1 ºC. La concentración de ozono disuelto en la fase líquida fue determinada por el método colorimétrico Índigo [13]. Luego de 5 min de exposición, la concentración de ozono fue de 5,1 ± 0,1 mg $O_3.L^{-1}$, la cual permaneció constante hasta el final del proceso.

Se consideraron dos controles: el fruto fresco (FF, fruto sin lavar) y el fruto sumergido en agua destilada burbujeada sólo con oxígeno (generador de ozono apagado) durante 10 min (control O_2 10 min) para diferenciar el efecto del ozono *per se* respecto al lavado ocasionado por la agitación de los frutos dentro de la columna.

2.3 Almacenamiento de las muestras

Inmediatamente después de los tratamientos los frutos fueron secados con papel absorbente y almacenados en bandejas plásticas con tapa de polipropileno de alta densidad (permeable al aire) a 4 ± 1 ºC durante 15 días.

2.4 Medición del color

El color de los frutos de arándano fue medido con un espectrofotómetro triestímulo de reflectancia (Minolta Co., Modelo CM-700-d, Japón), con un iluminante D65 y 2º de ángulo de observador. Se utilizaron 30 muestras independientes para cada tratamiento y se tomaron dos mediciones en dos posiciones diferentes de la zona ecuatorial del fruto. Luego se calculó el valor promedio para obtener un valor para cada fruto. Se registraron los valores de las coordenadas de color del espacio CIE (X, Y, Z)

y los parámetros L*, a* y b* del espacio CIELab donde L* indica luminosidad, a* indica cromaticidad sobre el eje que va del rojo (+) al verde (-), y b* indica cromaticidad sobre el eje que va desde el amarillo (+) hasta el azul (-). A partir de estos valores numéricos, se calcularon las funciones de color "croma" (C*) y "ángulo de tono" (h*).

2.5 Obtención de los espectros por Espectroscopía Infrarroja por Transformada de Fourier (FT-IR)

Esta técnica fue utilizada para evaluar posibles modificaciones y/o interacciones en las ceras y/o la cutícula del fruto ocasionados por el tratamiento con ozono. Las mediciones fueron realizadas en un espectrómetro Spectrum 400 FT-IR/FT-NIR (Perkin Elmer Inc., Estados Unidos) con un accesorio de Reflectancia Total Atenuada (ATR) con cristal de ZnSe de tres reflexiones, con ángulo de incidencia de 45º.

Para cada grupo experimental (FF, control O_2 10 min, 5,1 mg $O_3.L^{-1}$ 10 min), se obtuvieron espectros de tres sets de muestras: frutos sin cera, frutos con cera (frutos enteros) y espectros únicamente de ceras.

Para la obtención de los espectros de los frutos sin cera, las muestras fueron limpiadas al menos dos veces con un algodón empapado en cloroformo dentro de una campana de ventilación y dejados en reposo 10 a 12 h para evaporar por completo el solvente. Por otro lado, los espectros de los frutos (con y sin cera) fueron obtenidos comprimiendo cada fruto (sin provocar la rotura del mismo) con una punta plana de manera tal de garantizar un contacto íntimo entre la muestra y el cristal. Finalmente, los espectros únicamente de ceras fueron obtenidos frotando varias veces el fruto sobre el cristal de ZnSe, de modo tal que la cera quedase adherida al mismo. Para cada condición se analizaron 12 (frutos completos) o 6 frutos (ceras y frutos sin cera) y los espectros fueron adquiridos en el modo reflectancia, entre 600 y 4000 cm^{-1}, de un promedio de 32 escaneos y con una resolución de 4 cm^{-1}. Se adquirió un espectro en aire (sin muestra) previo a la medición de cada sistema.

La localización y obtención de los números de onda de los picos, así como la corrección de la línea de base de los espectros se realizó mediante el programa Spectrum versión 6.3.5 (Perkin Elmer Inc., Estados Unidos). Dado que el cristal utilizado muestra una región de muy alta absorción entre 1900 y 2250 cm^{-1}, ésta fue substraída en todos los casos.

Los estudios mediante FT-IR se realizaron inmediatamente después de los tratamientos con ozono (día 0) y luego de 15 días de almacenamiento a 4 ± 1 ºC.

2.6 Análisis estadístico

Para el análisis quimiométrico se utilizó el programa The Unscrambler v9.7 (Camo Software AS, Noruega). Todos los espectros fueron pre-procesados utilizando la primera y segunda derivada, corrección de dispersión multiplicada (MSC) y normalización de vectores (NV). El análisis de datos se realizó mediante un análisis de componentes principales (PCA) donde en un primer paso se analizaron todos los espectros juntos: frutos con cera, frutos sin cera y sólo ceras, correspondientes a frutos frescos (FF), control O_2 10 min, 5,1 mg $O_3.L^{-1}$ 10 min (n=150). Posteriormente y para cumplir el objetivo de este trabajo, se utilizaron solamente los espectros de los frutos con

cera correspondiente a los FF, control O_2 10 min y 5,1 mg $O_3.L^{-1}$ 10 min (n=85). En todos los casos la calibración se llevó a cabo con el 75% de los datos, y el test de validación con el 25% de los datos restantes. Se utilizó la prueba t de Student para comparar la predicción predictiva del modelo.

Los datos correspondientes a la evaluación del color se analizaron mediante un análisis de varianza multivariado (MANOVA) mediante el programa Infostat v.2008 (InfoStat, Argentina). Se utilizó la prueba Hotelling corregida por Bonferroni en caso de encontrar diferencias significativas. Previo al análisis, se verificaron los requisitos de normalidad y homocedasticidad y se detectaron los valores anómalos mediante el análisis de las distancias de Mahalanobis. El nivel de significancia utilizado en todos los análisis fue 0,05.

3 Resultados

3.1 Color

En la Tabla 1 se presentan los valores promedio ± desviación estándar de los parámetros colorimétricos (L*, a*, b*) y funciones de color (C*, h*) de los frutos tratados y control durante el almacenamiento. Al día 0, la fruta fresca (FF) presentó un color azul y la presencia de CE se evidenció por su superficie opaca. Los valores negativos de b* indicaron un predominio del color azul, mientras que los valores de C* indicaron una baja saturación de color que explicaría el aspecto grisáceo del arándano, y el ángulo de tono (h) ubicó los frutos en la región azul. No se observaron diferencias significativas entre FF, control O_2 10 min y 5,1 mg $O_3.L^{-1}$ 10 min, mientras que los frutos sin CE mostraron valores significativamente menores de L* y mayores de a* y b*, asociados principalmente a la ausencia de la capa de ceras. Las diferencias entre frutos enteros ozonizados (5,1 mg $O_3.L^{-1}$ 10 min) y no ozonizados (FF y control O_2 10 min) no resultaron en general significativas en el período de almacenamiento estudiado, excepto en los frutos a los que se les removió previamente las CE.

Después de 15 días de almacenamiento, los parámetros de color de los FF mostraron cambios leves, pero no significativos respecto al día 0. Sin embargo, el almacenamiento refrigerado afectó significativamente el color de la fruta sin CE, control O_2 10 min y 5,1 mg $O_3.L^{-1}$ 10 min. Los cambios más severos se observaron en los frutos sin CE, mientras que el control O_2 10 min y los frutos ozonizados mostraron un comportamiento intermedio.

En general, el tratamiento con ozono no afectó negativamente el color superficial de los arándanos con respecto a los frutos sin tratar (FF), ya sea inmediatamente después del tratamiento (día 0) o después de 15 días de almacenamiento.

Tabla1. Valores promedio y desviación estándar de los parámetros colorimétricos y funciones de color de arándanos control y tratados con ozono en fase acuosa almacenados 15 días a 4 ± 1 ºC. Se incluye a modo comparativo los valores correspondientes a frutos frescos (sin tratar) a los cuales se les removió las ceras epicuticulares (FF sin CE). Diferente letra entre filas indican diferencias significativas (n=30).

Día	Tratamiento	L*	a*	b*	C*	h*	
0	Fruta fresca (FF)	28,1 ± 2,9	0,09 ± 0,32	-3,7 ± 1,3	3,7 ± 1,2	272,5 ± 7,5	**def**
	Control O_2 10 min	27,3 ± 1,8	0,04 ± 0,26	-3,8 ± 0,8	3,8 ± 0,8	270,8 ± 4,1	**e**
	5.1 $mgO_3.L^{-1}$ 10 min	27,1 ± 2,3	-0,03 ± 0,31	-3,5 ± 1,0	3,5 ± 1,0	270,8 ± 6,4	**e**
	FF sin CE	22,0 ± 1,0	0,35 ± 0,31	-1,0 ± 0,4	1,1 ± 0,4	288,9 ± 14,3	**a**
5	Fruta fresca (FF)	29,1 ± 2,6	-0,03 ± 0,17	-3,8 ± 1,4	3,8 ± 1,4	270,1 ± 4,3	**d**
	Control O_2 10 min	27,3 ± 1,6	-0,02 ± 0,10	-3,4 ± 1,0	3,4 ± 1,0	269,9 ± 2,3	**def**
	5.1 $mgO_3.L^{-1}$ 10 min	27,5 ± 2,0	-0,12 ± 0,20	-3,4 ± 0,9	3,4 ± 0,9	268,5 ± 3,7	**def**
	FF sin CE	23,1 ± 0,8	0,22 ± 0,59	-1,2 ± 0,6	1,3 ± 0,7	281,2 ± 17,1	**ac**
10	Fruta fresca (FF)	29,0 ± 2,4	-0,05 ± 0,12	-3,8 ± 1,2	3,8 ± 1,2	269,7 ± 2,9	**d**
	Control O_2 10 min	27,9 ± 1,7	0,06 ± 0,39	-3,6 ± 1,0	3,6 ± 1,0	271,5 ± 6,5	**def**
	5.1 $mgO_3.L^{-1}$ 10 min	26,7 ± 1,7	-0,12 ± 0,12	-3,0 ± 1,0	3,0 ± 1,0	267,9 ± 2,0	**ef**
	FF sin CE	23,3 ± 0,6	0,15 ± 0,24	-1,0 ± 0,5	1,1 ± 0,5	279,5 ± 13,6	**c**
15	Fruta fresca (FF)	28,3 ± 2,3	0,03 ± 0,26	-3,4 ± 1,2	3,4 ± 1,2	270,9 ± 4,2	**df**
	Control O_2 10 min	28,3 ± 2,1	0,59 ± 0,93	-3,5 ± 0,9	3,6 ± 0,9	279,2 ± 14,2	**bf**
	5.1 $mgO_3.L^{-1}$ 10 min	26,9 ± 2,0	0,26 ± 0,95	-2,9 ± 0,9	3,0 ± 0,9	275,3 ± 17,6	**bf**
	FF sin CE	23,3 ±1,0	0,02 ± 0,10	-1,1 ± 0,4	1,13 ± 0,4	272,2 ± 5,8	**c**

3.2 Espectros FT-IR de arándanos tratados y control: análisis de componentes principales

Como se mencionó anteriormente, se estudiaron tres grupos de espectros (fruta completa, fruta sin cera y ceras epicuticulares) para cada tratamiento (FF, control O_2 10 min y 5,1 mg $O_3.L^{-1}$ 10 min). En la Figura 1 se muestra la variabilidad explicada y el número de componentes principales luego de aplicar las distintas metodologías de pre-procesamiento de los espectros. La normalización vectorial mostró un mejor rendimiento, ya que con sólo 3 componentes principales logró explicar el mayor porcentaje de la variabilidad en la calibración y validación.

La Figura 2 muestra las dos componentes principales más significativas de los espectros procesados mediante normalización vectorial (a) y la primera derivada (b). Ambas técnicas lograron separar los espectros de las ceras. Sin embargo, la normalización vectorial no logra una buena separación entre los tres grupos de muestras (Figura 2a). En cambio, con la primera derivada se obtuvo una buena separación entre los grupos experimentales, aunque para ello implicó una componente principal adicional.

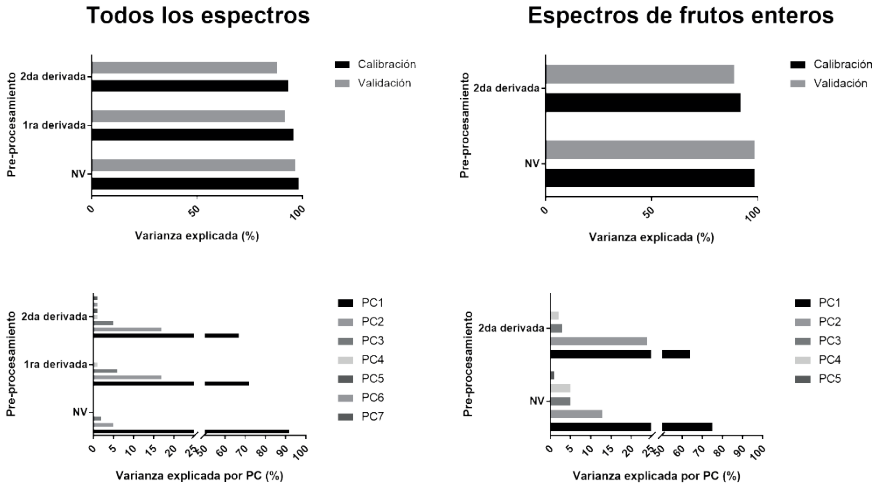

Fig.1 Efecto del pre-procesamiento en la explicación de la varianza y número de componentes principales (PC) de los espectros de fruta entera, ceras epicuticulares (CE) y fruta sin ceras de frutos sin tratar (FF), control O_2 10 min y ozonizados (5,1 mgO_3.L^{-1} 10 min). *NV: normalización vectorial. Se utilizaron entre 3048 y 3084 variables.

Por otro lado, la Figura 2b reveló que las diferencias entre los grupos de muestras (frutos enteros, sin ceras y sólo ceras) eran mucho mayores que las diferencias producidas por los tratamientos (FF, control O_2 10 min y 5,1 mg O_3.L^{-1} 10 min). Luego, se realizó un segundo PCA incluyendo sólo las frutas enteras de arándanos frescos (FF), control O_2 10 min y 5,1 mg O_3.L^{-1} 10 min, utilizando los dos mejores métodos de preprocesamiento; estos resultados se muestran en la Figura 3. Una vez más, la normalización vectorial explicó un mayor porcentaje de variabilidad que la primera derivada, a pesar de utilizar una componente principal más. Sin embargo, la Figura 3 reveló que la normalización vectorial no pudo separar la fruta ozonizada de las muestras FF y de control O_2 10 min (Figura 3a). En cambio, la primera derivada diferenció claramente entre las muestras tratadas con ozono, control O_2 10 min y FF, estas dos últimas comparten características espectrales comunes (Figura 3 b). Al analizar las cargas de las muestras procesadas mediante la primera derivada, se identificaron algunos números de onda, cuya mayor contribución correspondería al estiramiento asimétrico y simétrico de CH_2 a 2917 y 2850 cm^{-1}, respectivamente.

El alto poder oxidativo del ozono podría afectar las ceras epicuticulares, lo cual se evidenciaría en las diferencias encontradas en los espectros y revelado en el análisis de PCA (Figura 3b). Sin embargo, es interesante resaltar que el ozono no eliminó/removió completamente las ceras epicuticulares como puede observarse en las Figuras 2 y 4, en donde se muestra una buena superposición entre las muestras ozonizadas, control O_2 10 min y FF, coincidentemente con los resultados obtenidos en el estudio de color (Tabla 1).

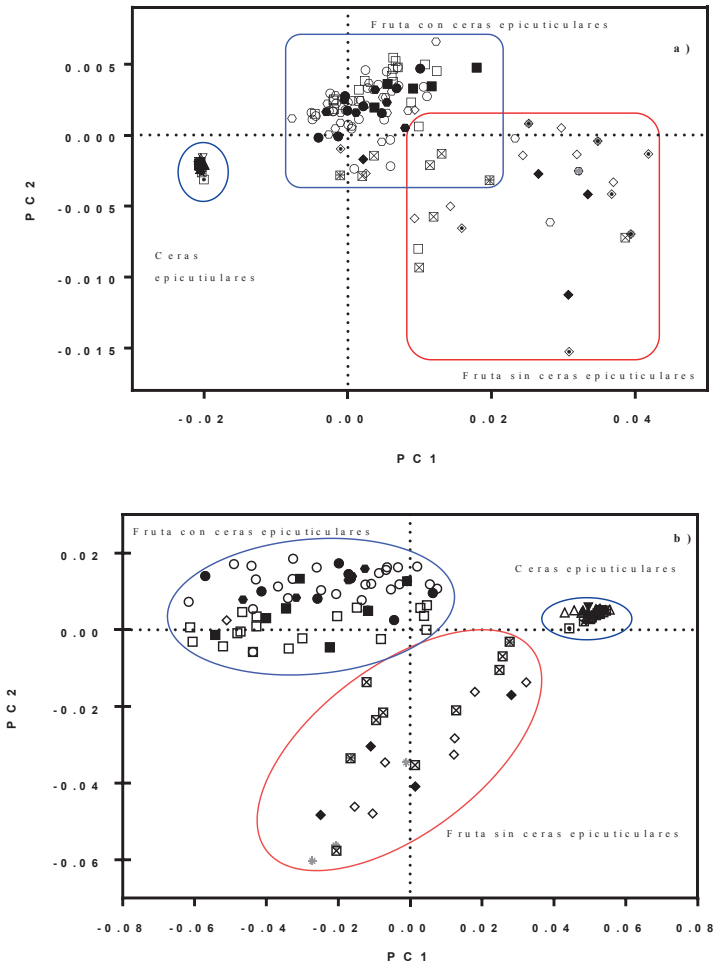

Fig.2. Análisis de componentes principales (PCA) luego del pre-procesamiento por medio de normalización vectorial (a) y 1[ra]derivada (b) de los espectros. Frutos enteros: frescos (○,●), control O_2 10 min (⬭,⬬), tratados 5,1 $mgO_3.L^{-1}$ 10 min (□,■). Ceras epicuticulares: frescos (△,▲), control O_2 10 min (▽,▼), tratados 5,1 $mgO_3.L^{-1}$ 10 min (▣,★). Frutos sin CE: frescos (◇,◆), control O_2 10 min (◈,✳), tratados 5,1 $mgO_3.L^{-1}$ 10 min (☒,⨯), siendo (calibración, validación), respectivamente. Los datos incluyen días 0 y 15 de almacenamiento.

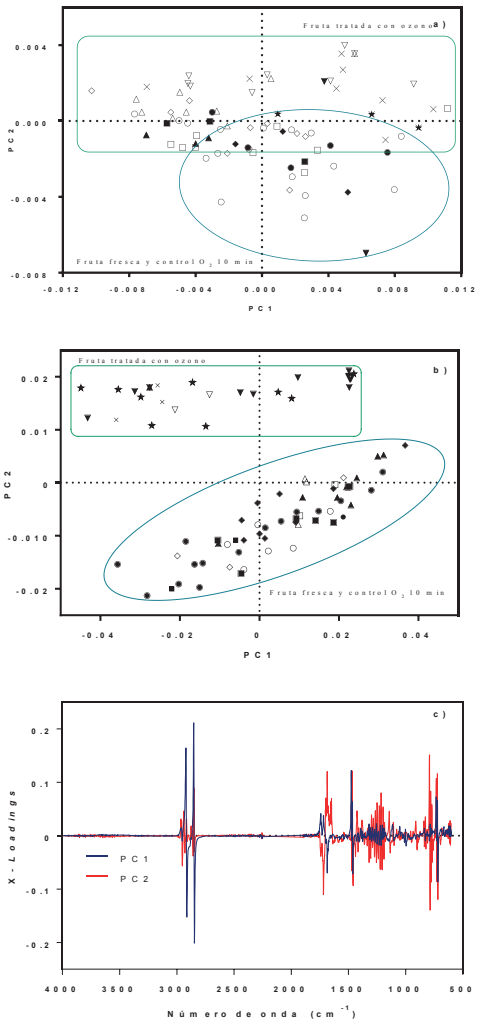

Fig.3.PCA de espectros de fruta entera: sin tratar (FF), control O_2 10 min y tratadas 5,1 $mgO_3.L^{-1}$ 10 min a los 0 y 15 días de almacenamiento a 4 ±1 ºC, pre-procesados mediante normalización vectorial (a) y 1ra derivada (b,c).Puntajes de las componentes principales que explican el mayor porcentaje de variabilidad (a,b); X-puntajes vs número de onda de las componentes principales (PC1 y PC2, líneas gris y negra, respectivamente) (c). Para a y b: sin tratar (○●,△▲), control O_2 10 min (□■,◇◆) y 5,1 $mgO_3.L^{-1}$ 10 min (×★,▽▼) [a los 0 y 15 días de almacenamiento a 4 ±1 ºC, siendo calibración (símbolos sin relleno) y validación (símbolos rellenos), respectivamente].

3.3 Estudio FT-IR de las modificaciones moleculares ocasionadas por el tratamiento con ozono en las ceras epicuticulares de arándanos

En la Figura 4 se muestra una comparación detallada de los espectros de ceras epicuticulares y de frutos enteros tanto del control lavado y de los frutos ozonizados (control O_2 10 min y 5,1 mg $O_3.L^{-1}$ 10 min), al día 0. Los espectros de CE mostraron bandas características mencionadas en la Tabla 2. Las más importantes corresponden a triterpenoides pentacíclicos, β-dicetonas, aldehídos, alcoholes primarios y ácidos grasos (compuestos alifáticos de cadena larga), según lo reportado por [7] para ceras cuticulares de arándanos cultivar O'Neal. Las flechas de la Figura 4 indican las regiones de mayores diferencias entre los espectros de los frutos ozonizados y control O_2 10 min. El estudio mediante FT-IR reveló cambios ocasionados por el ozono en las ceras epicuticulares como así también en otros componentes de la cutícula: aparecieron nuevas bandas y hombros (1701, 1542, 801 cm^{-1}), como se señala en la Tabla 2; mientras que también se observaron corrimientos de algunas señales asignadas a CE (1464-1472 a 1468; 730 a 724; 1055 a 1101-1109; y otras desde 884-904 a 887-910; 762 a 755 cm^{-1}). Los alquenos son uno de los principales objetivos a ser oxidados por el ozono siguiendo el mecanismo de Criegee [14], los alcoholes primarios son oxidados a cetonas y los secundarios, a los aldehídos y grupos carboxílicos. En particular, la banda a 1701 cm^{-1} evidenciada en los frutos ozonizados podría atribuirse a la oxidación de alcoholes de cadena larga. Los alquenos, ácidos carboxílicos y cetonas no reaccionan con el ozono o bien, lo hacen de manera más lenta [14,15].

Los espectros de los frutos enteros mostraron grandes diferencias tanto en intensidad como en bandas con respecto a los espectros de las CE, en ambos casos frutos ozonizados o control (Figura 4). Estas contribuciones nuevas surgen de la presencia de otros componentes de la cutícula como la cutina. La cutina es un polímero lipídico y componente principal de la piel de las frutas y berries, que junto a las CE constituyen una barrera entre la planta y el ambiente [16,17]. Las principales diferencias con los espectros de las CE se observaron en las regiones: 2800-2500, 1700-1660, 1660-1500, 1428-1450, 1330-1170 y 1075-950 cm^{-1}. Sin embargo, también se observaron bandas en común, indicando la presencia de ceras en la membrana cuticular del fruto entero.

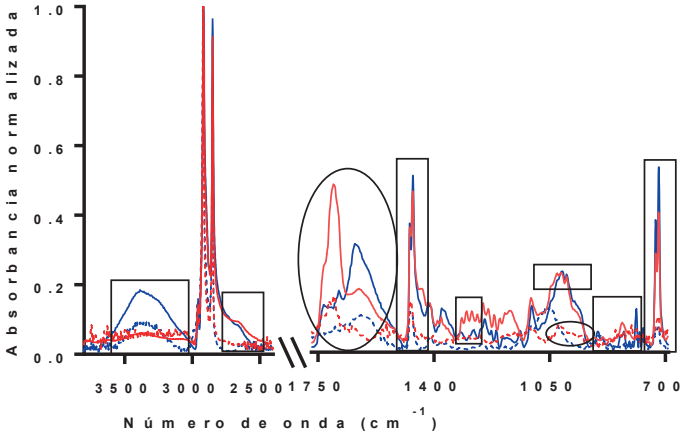

Fig.4. Espectros FT-IR de frutos ozonizados a (5,1 $mgO_3.L^{-1}$ 10 min) (líneas grises) y control $O_2$10 min (líneas negra). Las líneas continuas corresponden a espectros de los frutos enteros y las líneas punteadas a los espectros de ceras epicuticulares (CE). Los datos corresponden al día 0 de almacenamiento.

Tabla2. Asignación de señales a ceras epicuticulares (CE) y ceras + cutina de los espectros FT-IR obtenidos de ceras epicuticulares y de frutos enteros, respectivamente para control O_2 10 min y 5,1 $mgO_3.L^{-1}$ 10 min. h: hombro, +: aumento de intensidad relativa, a: ancho, d: doble. En negrita: por efecto del ozono (corrimiento, o aparición de nuevo pico u hombro)

Pico (cm^{-1})				Posible asignación	Componente de la cutícula	Referencias
CE		CE+cutina				
Control O_2 10 min	5,1 $mgO_3.L^{-1}$ 10 min	Control O_2 10 min	5,1 $mgO_3.L^{-1}$ 10 min			
1620 a	**disminución**	1634	**1626**	Estiramiento de C=C anillo aromático	Compuestos fenólicos	[18,19]
1464-1472	**1468**		1472	$-CH_2-$ tijereteo de cadenas de HC	Cutina, ceras	[18,20-22]
		1417	**1412**	Estiramiento C-C anillo	Cutina	[19]

1104	**1101-1109**					
Múltiples picos: 1075 1065 1956 1050 1037		1027	**998**		Triterpenoides pentacíclicos	[22]
884 (h de 890) 890 896 904	**887 (h de 893)** **893** **899** **910**				Ceras	
		825-836	**830**	C-H bending		
	801		**807**		**Por ozono**	
730	**724** (h de 720)	730		-CH_2- rocking	Ceras	[19,21, 23]
3382 a	-	3382+	3384	Grupo OH	Triterpenoides pentacíclicos Cutina	[19,20,22]
2958		2955		Estiramiento CH_3 cadenas alifáticas	Ceras	[19-22]
2917		2914		Estiramiento asimétrico de CH_2- Cadenas de HC	Ceras Cutina	[19-22]
2850		2848		Estiramiento simétrico CH_2-	Ceras	[19-21]
		2660 2830-2500 a	2660 (h)+ 2830-2500 a	Estiramiento C-H	Aldehídos Alcanos Estiramiento O-H de alcoholes	
		1732		Estiramiento C=O de ésteres	Cutina	[20,21]

1710 h		1710 h		Estiramiento C=O de carbonilo	Oxidación de alcoholes de cadena larga a aldehídos, ácidos carboxílicos o cetonas	[19]
		1686	1686 h	C=O...H	Cutina	[18]
1648	1648	1652 h		α β-cetonas insaturadas	B-dicetonas	[24,25]
		1463	1463&1454 h	-CH_2- tijereteo de cadenas de HC	Cutina, ceras	[19]
		1437	1437 +	Estiramiento simétrico (bending) de -CH_2-	Cutina	[19]
		Región 1330-1170 (8 y 11 picos, respectivamente)		1330 Vibración de anillo 1170 estiramiento asimétrico C-O-C Bending simétrico-CH_2- Estiramiento C-O & C-C (1115 y otros)	Cutina Cutina	[18,20,21, 26]
		1104	1105	Estiramiento simétrico C-O-C de éster	Cutina	[18,20]
		960 h	960 h de 998	C=C bending	Cutina	

4 Conclusiones

El tratamiento con ozono en fase acuosa (5,1 mg $O_3.L^{-1}$, 10 min) produjo cambios químicos en las ceras epicuticulares de los arándanos, como revelaron los espectros FT-IR. El efecto del ozono en las ceras se evidenció por la aparición de nuevas bandas asociadas al estiramiento del grupo carbonilo de la oxidación de alcoholes (1701 cm^{-1}), y corrimiento de otras asociadas al tijereteo (1464-1472 a 1468 cm^{-1}) y balanceo de grupos CH_2, entre otros. Estos cambios químicos podrían atribuirse de forma directa al ozono y no al efecto de lavado del proceso, ya que los espectros correspondientes al controlO_2 10 min mostraron características similares a la de los frutos sin tratar (FF) tanto al día 0 como después de 15 días de almacenamiento. Sin embargo, estas modificaciones podrían ser sutiles desde la óptica del consumidor ya que los cambios ocasionados por el ozono en las CE no afectaron el color de los frutos.

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Influencia de cultivos autóctonos iniciadores de la fermentación alcohólica sobre atributos sensoriales de vinos Patagónicos

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Resumen. En este trabajo se evaluó a escala piloto la aptitud enológica de levaduras autóctonas de la región patagónica y su influencia sobre el color y *flavour* del vino. Mostos patagónicos Malbec se inocularon con cultivos puros de cepas de *Saccharomyces cerevisiae* autóctonas Sc F8 y Sc M16 y comercial Sc F15 (control), y con el cultivo mixto autóctono Sc F8 y *Pichia kudriavzevii* P15 (Sc F8+P15, cocultivo) durante las vendimias 2015 y 2017. Las cinéticas fermentativas se siguieron por evolución de los ºBmé, la evaluación fisicoquímica de los vinos y los parámetros relacionados con el color (intensidad y tinte) se realizaron siguiendo los métodos del INV y espectrofotometría UV-V y el sensorial mediante análisis descriptivo y prueba de preferencias de consumidores. Todos los vinos resultaron normales y secos, pero los elaborados con los cultivos puros autóctonos mostraron diferencias con los del comercial en sus parámetros de color que pueden relacionarse con un mayor contenido de copigmentos (hipercromía, vendimia 2015) y de pigmentos resistentes al SO_2 (hipsocromía, vendimia 2017). Adicionalmente, los cultivos autóctonos puros potenciaron los aromas a frutos rojos y especiados, propiedad que conservó el cocultivo. La inclusión de P15 en el cultivo iniciador adicionalmente mejoró la sensación en boca (acidez y dulzor) resultando sus vinos (vendimias 2015 y 2017) y los elaborados con el cultivo mixto Sc F8 (vendimia 2017) preferidos por los consumidores. Los cultivos iniciadores autóctonos F8 y F8+P15 constituyen una valiosa herramienta para la diferenciación y el agregado de valor de los vinos regionales.

Palabras clave: ***Saccharomyces cerevisiae*, *Pichia kudriavzevii*, color, aroma, gusto.**

1. Introducción

El vino es, exclusivamente, la bebida resultante de la fermentación alcohólica (FA), completa o parcial, de uvas frescas, estrujadas o no, o de mosto de uva [1] y su composición química es la base de sus atributos sensoriales y en consecuencia de su calidad.

De los numerosos factores que afectan la calidad del vino, el sustrato y la biota microbiana imperante durante el proceso de vinificación, son en ese orden, los de mayor significación [2].

La vinificación es un proceso ecológicamente complejo que involucra una fermentación primaria, la alcohólica (FA), conducida por las levaduras y una fermentación secundaria y opcional, la maloláctica (FML), llevada a cabo por las bacterias del ácido láctico (BAL) [3]. Las numerosas interacciones celulares/bioquímicas que se establecen entre individuos de las diferentes especies de levaduras y BAL participantes de la vinificación [4] pueden producir vinos redondos y de gran complejidad aromática, pero también ocasionar metabolitos o efectos indeseables, como *off flavors*, compuestos perjudiciales para la salud y paradas o retrasos de la fermentación [5]. Esta impredecibilidad es la mayor desventaja de la elaboración de vinos por fermentaciones naturales a nivel industrial [6]. El control de la biota microbiana asociada al proceso fermentativo mediante la inoculación del mosto de uva con cultivos iniciadores es una práctica enológica de rutina en bodega tendiente a resolver este problema [7].

Por la importancia de la FA, la tecnología de los cultivos iniciadores centró inicialmente su atención en las levaduras, especialmente en la biodiversidad intraespecífica de *Saccharomyces cerevisiae,* la levadura vínica por excelencia [7]. Más recientemente la búsqueda se orientó a otras especies de levaduras pertenecientes a géneros diferentes de *Saccharomyces,* asociadas a la fase inicial de la fermentación espontánea de los mostos y denominadas colectivamente levaduras non-*Saccharomyces* [8]. Por sus características metabólicas particulares, individuos de estas especies utilizados en la forma de cultivos adjuntos de *S. cerevisiae* pueden proporcionar soluciones tecnológicas a problemas específicos (reducción de la acidez, del contenido alcohólico, desarrollo de color, entre otros) así como mejorar la calidad sensorial y /o sanitaria del producto [8-10].

En la enología actual, la tendencia mundial es el uso de cultivos iniciadores de la fermentación alcohólica (FA) constituidos por cepas de levaduras autóctonas de la propia región productora. Estos cultivos autóctonos, adaptados a las características agroecológicas de su región y respetuosos de su *terroir* microbiano, presentan mayor capacidad de competencia que los cultivos foráneos para controlar exitosamente el proceso [11]. Adicionalmente, utilizados en la forma de cultivos múltiples (más de una

cepa de *Saccharomyces*) o mixtos (cepas *Saccharomyces* y non-*Saccharomyces*) son capaces de otorgar a los vinos características sensoriales de aquellos elaborados por fermentaciones espontáneas/naturales exitosas, aunque bajo condiciones controladas del proceso [6], permitiendo expresar en los vinos las notas organolépticas distintivas de su terroir [12].

La región del Comahue (Patagonia norte) conforma la región vitivinícola más austral de la Argentina y una de las más australes del mundo; la formulación y aplicación de cultivos iniciadores regionales, hoy inexistentes en el mercado, permitirá resolver problemáticas del sector vitivinícola regional, favoreciendo la elaboración de productos de calidad controlada y diferencial, en los que se expresen las características de su terruño, muy ventajosas para el desarrollo de una viticultura de calidad enológica *premium* [13]. En este trabajo se presentan y discuten resultados relacionados con las calidades de vinos tintos de la variedad Malbec elaborados a escala piloto (200 L) mediante vinificaciones conducidas por cultivos puros y mixtos constituidos por levaduras autóctonas de esta región de las especies *S. cerevisiae* y *Pichia kudriavzevii* [14] poniendo el foco en los atributos color y *flavour* (aroma y gusto), los más apreciados por el consumidor al momento de la elección de un vino [15]. La capacidad de la cepa de *P. kudriavzevii* de consumir ácido L(−) málico [16] podría, adicionalmente, ayudar a resolver la elevada acidez relativa de los vinos de la región del Comahue respecto de aquellos elaborados en las otras regiones vitivinícolas del país debido al alto contenido de éste ácido en los mostos de uva patagónicos [17].

2. Materiales y métodos

2.1 Microorganismos

Se utilizaron cepas autóctonas de la Patagonia de las especies *S. cerevisiae* F8 (Sc F8) y M16 (Sc M16) y *P. kudriavzevii* (ex *Issatchenkia orientalis*) I15 (P15) seleccionada por sus características metabólicas de interés enológico [14] (del Mónaco *et al*. 2016) y la cepa comercial *S. cerevisiae* F15 (Sc F15) de Laffort, mayoritariamente usada en bodegas patagónicas para vinificaciones en tinto.

2.2 Vinificaciones

Se realizaron a escala piloto (200L) durante las vendimias 2015 y 2017. Mostos industriales Malbec se inocularon con cultivos puros de la cepa autóctona Sc F8, y de la

comercial Sc F15 y con el cultivo mixto F8 + P15 en la forma de cocultivo (CoC, inoculación simultánea en una relación 1/100 cél/mL) durante la vendimia 2015; en la vendimia 2017 adicionalmente se ensayó la cepa autóctona Sc M16 en la forma de cultivo puro. Las densidades celulares iniciales de los inóculos en los mostos estuvieron en el orden de ~10^7 cél/mL. Las FAs se desarrollaron a 23±2°C hasta sequedad de los mostos (azúcares reductores totales ≈2 g L^{-1}). En las vinificaciones 2015 la FML se desarrolló espontáneamente controlándose la evolución mediante la determinación enzimática del contenido del ácido L (-) málico. En las vinificaciones 2017 se inhibió el desarrollo de la FML por adición de elevadas concentraciones de SO_2 (100 ppm). Los vinos jóvenes se estabilizaron, se ajustaron en su concentración de SO_2 y se embotellaron. Con el fin de realizar análisis microbiológicos y fisicoquímicos se tomaron muestras de mostos en los estadios iniciales, medios y finales de las FA y de la FML, cuando correspondió (Vendimia 2015).

2.3 Análisis de los vinos

Fisicoquímico. La evaluación fisicoquímica de los vinos se realizó utilizando la metodología oficial del Instituto Nacional de Vitivinicultura (INV). El análisis estadístico de los datos se realizó mediante ANOVA y ensayo de Tukey HSD considerándose significativas diferencias con $p<0,05$. El análisis de parámetros de color en los vinos obtenidos al finalizar la FA se llevó a cabo en base a las medidas de absorbancia realizadas a tres longitudes de onda λ_{420nm}, λ_{520nm} y $\lambda_{620\ nm}$,. A partir de dichos valores pueden determinarse diferentes parámetros relacionados al atributo del color: Intensidad de Color ($A_{420nm}+A_{520nm}+A_{620nm}$), Tinte ($A_{420nm}/A_{520nm}$) e Índice de color IC = (intensidad de color/tinte *1000). En los vinos 2017 los parámetros de color se evaluaron antes y 48h después del sulfitado.

Sensorial. Con el objetivo de describir las muestras en forma cualitativa y cuantificar la intensidad de los distintos atributos sensoriales se realizó un análisis sensorial descriptivo de los vinos utilizando para ello una escala de 1=no intensidad a 10=intensidad extrema. Participaron nueve (9) evaluadores altamente entrenados. Cada evaluador recibió una muestra etiquetada con un código de tres (3) dígitos elegidos al azar. La presentación de las muestras se realizó en forma monádica para evitar comparaciones entre muestras. Se utilizó un diseño estadístico de bloques completos al azar en donde cada

evaluador ofició de bloque. Cada panelista recibió las muestras en un orden preestablecido y diferente al de los demás. Se realizaron tres (3) repeticiones en dos días diferentes en donde se varió tanto el orden de presentación para cada evaluador como los códigos de tres dígitos para reducir la posibilidad de resultados tendenciosos y el efecto posicional. Las muestras fueron servidas en copas normalizadas de color negro [18] a temperatura ambiente de 20±2ºC. En cada copa se sirvieron 30 ml de vino. Se instruyó a los evaluadores que indicaran la intensidad de cada atributo sensorial tanto de la fase visual, olfativa y gustativa. A fin de ayudar a los evaluadores a recordar los atributos pautados, se utilizaron estándares preparados en un vino base Malbec 2017 elaborado en el laboratorio de microvinificación de la EEA INTA Alto Valle [19]. Para reducir la variabilidad en la medición de las intensidades de los atributos, se utilizaron patrones de los atributos de acidez, dulzor, amargor, astringencia cuyas intensidades fueron consensuadas por el panel en trabajos previos realizados en 2018. Para interpretar los resultados se determinaron las medias de los valores asignados a la intensidad de los atributos sensoriales y se realizó un análisis de la varianza (ANOVA) y un análisis de componentes principales utilizando el software Infostat [20].

2.4 Prueba de Preferencia de Consumidores

Se realizaron en Bariloche a la Carta 2016 (vinos 2015) y durante la 39 Edición de Fiesta de la Vendimia 2018 (vinos 2017). En estas pruebas los diferentes vinos elaborados se identificaron con diferentes letras A, B, C, D debiendo el consumidor asignarle a cada vino un valor 1, 2, 3 o 4 según su preferencia. Uno, el preferido en primer lugar, dos en segundo lugar, etc. En esta degustación a ciegas, el promedio obtenido para cada vino es más cercano a uno cuanto mayor es su preferencia por el consumidor. El análisis estadístico de los datos se realizó utilizando un modelo lineal generalizado y prueba de comparaciones múltiples de Di Rienzo, Guzmán y Casanoves (DGC) [21]. El análisis se realizó a través del software INFOSTAT [20] como interfaz gráfica para el paquete NLMER de R [22].

3. Resultados y discusión

La Tabla 1 muestra los parámetros fisicoquímicos de importancia enológica de vinos Malbec elaborados con cultivos iniciadores puros Sc F8 y Sc M16 y mixto F8+P15 autóctonos, así como con el cultivo comercial Sc F15 durante la Vendimia 2015.

Todos los vinos resultaron normales y sus contenidos en azúcares reductores totales (ART) se encuentran dentro de los límites aceptados para ser clasificados como vinos secos (ART≤2g/L). Las concentraciones de metanol en los vinos fueron siempre <0,25 mg/L y las de carbamato de etilo en todos los casos estuvieron por debajo del límite de detección de métodos utilizado por el INV (15µg/L) (datos no mostrados), no observándose diferencias significativas de los parámetros evaluados entre vinos excepto en los relacionados con el color, evidenciando una influencia significativa de las cepas conductoras de la FA sobre este atributo.

Consistente con lo reportado en investigaciones previas con las variedades Pinot noir y Merlot [23], los vinos elaborados en el 2015 con la variedad Malbec (Tabla 1) y el cultivo indígena Sc F8 presentan un índice de color (IC) significativamente mayor (efecto hipercrómico) que los elaborados con su control Sc F15. Esta hipercromía se explica por un aumento de la absorbancia de estos vinos a 520 nm y 620 nm (efecto batocrómico) sin cambios en la absorbancia a 420 nm (datos no mostrados), que determinan un aumento significativo en la intensidad de color y concomitantemente una disminución del tinte (Tabla 1).

Tabla 1. Caracterización fisicoquímica y evaluación sensorial de vinos obtenidos a partir de mostos tintos regionales variedad Malbec- vendimia 2015, conducidas por cultivos puros de *S. cerevisiae* F8 (Sc F8) y F15 comercial (Sc F15) y cultivo mixto Sc F8 + *P. kudriavzevii* P15 (CoC)

Evaluación Fisicoquímica	**Sc F15**	**Sc F8**	**CoC**	**P**
ART (g/L)	2,00±0,38	1,80±0,51	1,85±0,78	ns
Etanol (% v/v)	15,10±0,10	15,00±0,80	14,80±0,10	ns
pH	3,93±0,04	3,90±0,02	3,87±0,18	ns
AT†	4,77±1,07	4,61±0,14	4,86±0,21	ns
AV^{++}	0,75±0,03	0,77±0,05	0,73±0,00	ns
Ac. L-málico (g/L)	0,42±0,23	0,53±0,11	0,41±0,06	ns
Glicerol (g/L)	10,46±0,26	9,45±0,35	10,56±0,31	ns
SO_2 Total (ppm)	20±9	15±7	16±4	ns
SO_2 Libre (ppm)	6±1	6±2	6±2	ns

Índice de Color	1243±33[b]	2056±114[a]	1092±62[b]	<0,01
Intensidad Color	0,92±0,10[b]	1,38±0,20[a]	0,80±0,09[b]	<0,05
Tinte	0,74±0,04[a]	0,65±0,00[b]	0,69±0,03[ab]	<0,05

ART: Azúcares Reductores Totales (g/L); † Acidez Titulable expresada en Ácido Tartárico (g/L); †† Acidez Volátil, expresada en Ácido Acético (g/L); Subíndices diferentes indican diferencias significativas dentro del lote de datos de cada fila analizados por Anova y Test Tukey HSD n=2

El origen del color rojo de los vinos tintos proviene de las antocianinas (antocianidinas glicosiladas en el C3), compuestos particularmente inestables en sus formas libres [24, 25]. La estabilización del color se logra por asociación de moléculas de antocianinas consigo mismas o con otros constituyentes del vino, mayoritariamente compuestos fenólicos flavonoides y no flavonoides, a través de interacciones no covalentes (copigmentación), por formación de enlaces covalentes (pigmentos poliméricos) y por formación de nuevos pigmentos colorantes (piranoantocianinas) [25]. En general, la copigmentación es el mecanismo más importante de estabilización del color en los vinos jóvenes y está asociada con un incremento de la intensidad (efecto hipercrómico) y a un viraje hacia tonalidades más azuladas (efecto batocrómico) del color rojo del vino tinto (disminución del tinte). La concentración de copigmentos depende de la composición fenólica y de las relaciones molares de copigmento/pigmento que de forma particular se establecen en un vino. Si bien los complejos de copigmentación se forman con mucha facilidad [26], también se disocian fácilmente ante ciertas condiciones del medio (aumento de la proporción de ciertos co-solventes como el etanol y otros alcoholes del vino o el ácido acético) derivados de las actividades metabólicas de las levaduras [25]. En este contexto, la hipercromía de los vinos elaborados con la levadura autóctona Sc F8 podría estar relacionado con un mayor contenido de pigmentos promovido por las condiciones del medio vino generado por un metabolismo particular de esta cepa que favorece la extracción de antocianinas y copigmentos o la estabilización de éstos.

Por su parte, los vinos elaborados con el CoC (F8+P15) mostraron IC e intensidad de color significativamente menores que sus vinos controles (ScF8), perdiéndose el efecto hipercrómico como el batocrómico producido por el cultivo puro. Esta pérdida de color es consistente con pérdidas en el material colorante atribuible a la actividad β-glucosidasa (β-GL) del cultivo adjunto *P. kudriavzevii* P15 [16].

Estas diferencias químicas en el color fueron consistentes con la apreciación de este atributo en el análisis sensorial cualitativo (Figura 1) que reportó una mayor intensidad en los vinos elaborados con la cepa de *S. cerevisiae* autóctona que en los elaborados con la cepa comercial y una disminución de la misma por el agregado del cultivo adjunto P15. Las tablas 2 y 3 muestran los autovectores y las correlaciones de los componentes principales con las variables originales de la Figura 1.

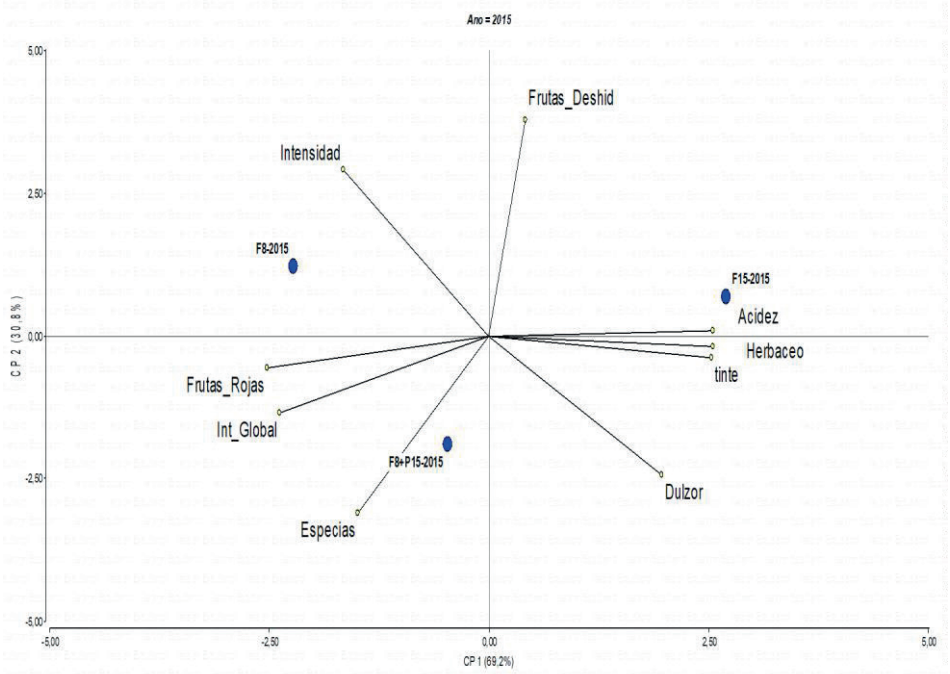

Figura 1: Componentes principales del análisis sensorial descriptivo de los vinos 2015. Intensidad: intensidad de color. Int_Global: intensidad global aroma; Frutas Rojas, Frutas Deshid (Deshidratadas) Especias, Herbáceo: notas aromáticas. Acidez y Dulzor, gusto. Las variables graficadas presentaron diferencias significativas (ANOVA $p<0,05$).

Tabla 2: Autovectores Figura 1

Variables	e1	e2…..
Intensidad	-0,26	0,46
Tinte	0,40	-0,06
Int_Global	-0,38	-0,21
Frutas_Rojas	-0,40	-0,09
Frutas_Deshid	0,07	0,59
Herbaceo	0,40	-0,03
Especias	-0,23	-0,49
Dulzor	0,31	-0,38
Acidez	0,40	0,02

Tabla 3: Correlaciones con las variables originales Figura 1

Variables	CP 1	CP 2
Intensidad	-0,65	0,76
Tinte	0,99	-0,10
Int_Global	-0,94	-0,35
Frutas_Rojas	-0,99	-0,15
Frutas_Deshid	0,16	0,99
Herbaceo	1,00	-0,05
Especias	-0,58	-0,81
Dulzor	0,77	-0,64
Acidez	1,00	0,03

En relación al aroma, los vinos elaborados con los cultivos autóctonos puro y mixto presentaron notas a frutas rojas frescas (4,00±0,44 y 3,81±0,34) y especiadas (2,4±0,17 y 2,9±0,34) significativamente mayores y notas herbáceas (2.90±0,14 y 3,00±0,21) significativamente menores que los elaborados con el cultivo comercial (3,11±0,20, 2,00±0,33 y 3,5±0,14). Adicionalmente, los elaborados con el CoC presentaron menor acidez y mayor dulzor en boca que su control (Figura 1) y fueron preferidos por los consumidores (Tabla 4).

Tabla 4: Prueba de Preferencia de Consumidores por los Vinos 2015 elaborados con la variedad Malbec y FAs conducidas por los cultivos iniciadores autóctonos puro (F8) y mixto (F8+P15) y por el comercial (F15)

Cultivo iniciador FA	Media	E.E.	
F15	2,20	0,18	A
F8	2,10	0,20	A
F8+P15	1,68	0,25	B

Medias con una letra común no son significativamente diferentes (p > 0,10), n=71

La calidad sensorial de los vinos jóvenes de variedades aromáticamente neutras como los aquí presentados está significativamente influenciada por la calidad de la biota de levaduras, pero también y aunque en menor grado, por las BAL. Los contenidos de ácido málico, sin diferencias y relativamente bajos en los tres vinos, y el pH elevado de todos éstos (Tabla 1) indican un desarrollo espontáneo de la FML en todas las vinificaciones, no pudiéndose descartar una potencial influencia de la biota BAL sobre las propiedades sensoriales de los vinos 2015. Con el objeto de inhibir el desarrollo espontáneo de la FML y obtener resultados conclusivos respecto de influencia de los cultivos

de levaduras autóctonas y comerciales sobre la calidad sensorial de los vinos, durante la Vendimia 2017, una vez finalizada la FA los vinos fueron sulfitados.

Todos los perfiles fisicoquímicos de los vinos obtenidos en la vendimia 2017 corresponden a vinos normales y secos (Tabla 5), pero la sulfitación deliberada realizada para impedir el desarrollo de la FML determinó que los vinos elaborados con los tres cultivos puros presentaran una mayor acidez titulable y un menor pH que sus homólogos 2015, diferencias que pueden relacionarse con su mayor contenido de ácido málico. Por el contrario, los vinos elaborados con el cultivo mixto presentaron un contenido de ácido málico significativamente menor y un pH significativamente mayor que su control (Sc F8) y similares a los obtenidos en los vinos 2015 elaborados con el mismo CoC. Este resultado es consistente con la capacidad de la cepa P15 de asimilar ácido málico, propiedad señalada en la Introducción y por la que fuera seleccionada [16]. El cultivo mixto representa una herramienta valiosa y alternativa a la FML para la deacidificación biológica de los vinos.

En relación al contenido de glicerol (Tablas 1 y 5) y a la calidad aromática de los vinos, los resultados obtenidos en el 2017 son consistentes con los del 2015 (Figuras 1 y 2) por lo que estas características pueden relacionarse con la calidad de las cepas de levaduras responsables de conducir la FA. Los vinos elaborados con los cultivos iniciadores puros autóctonos (Sc F8 y Sc M16) y mixto presentaron notas aromáticas a frutos rojos y especias significativamente mayores y herbáceas significativamente menores que los elaborados con el cultivo comercial, y de intensidad similar a las observadas en el 2015. Adicionalmente, el vino elaborado con el CoC presentó la menor acidez y el mayor dulzor entre los vinos evaluados, propiedades que pueden relacionarse con un menor contenido de ácido L(-) málico y mayor contenido de glicerol en este vino que en el control (Sc F8) y en el elaborado con Sc M16, respectivamente (Tabla 5).

Tabla 5: Caracterización fisicoquímica de los vinos elaborados con cultivos iniciadores indígenas puros Sc F8, Sc M16 y mixto F8 +P15 en la forma de CoC y con el cultivo foráneo comercial Sc F15 en la Vendimia 2017 con la variedad Malbec

	Malbec 2017				
Evaluación Fisicoquímica	**Sc F15**	**Sc M16**	**Sc F8**	**Sc F8+P15**	p
ART (g/L)	2,00±0,38	1,85±0,18	1,80±0,31	1,61±0,21	ns
Etanol (% v/v)	11,94±1,56	13,26±0,27	13,81±0,42	13,42±0,22	ns

pH	3,67±0,03^{a}	3,66±0,02^{a}	3,68±0,02^{a}	3,83±0,02^{b}	<0.05
Acidez titulable †	6,36±0,20^{b}	6,17±0,11^{b}	5,95±0,14^{ab}	5,75±0,21^{a}	<0.05
Acidez volátil ††	0,55±0,13	0,55±0,08	0,45±0,09	0,48±0,11	ns
Ácido málico (g/L)	3,14±0,15^{b}	2,56±0,25^{b}	3,77±0,61^{b}	0,73±0,31^{a}	<0.01
Glicerol (g/L)	10,42±0,22^{b}	9,41±0,19^{a}	9,38±0,11^{a}	10,71±0,11^{b}	<0.05
Índice de color	2234±65^{a}	2694±54^{b}	2779±31^{b}	2473±45^{a}	<0.01
Intensidad color	1,270±0,046^{a}	1,969±0,037^{c}	1,979±0,087^{c}	1,569±0,057^{b}	<0.01
Tinte	0,598±0,030^{a}	0,733±0,017^{b}	0,708±0,14^{b}	0,634±0,022^{a}	<0.05
SO_2 Total (ppm)	105±10	95±8	101±11	89±9	ns
SO_2 Libre (ppm)	45±4	40±3	42±3	42±4	ns
Índice de color	1990±58^{b}	2192±63^{b}	1936±45^{b}	1582±60^{a}	<0.01
Intensidad color	1,194±0,100^{a}	1,756±0,124^{b}	1,677±0,114^{b}	1,215±0,109^{a}	<0.01
Tinte	0,600±0,056^{a}	0,801±0,043^{c}	0,861±0,042^{c}	0,768±0,061^{b}	<0.05

† Expresada como ácido tartárico (g/L); †† expresada como ácido acético (g/L). En los vinos 2017 se inhibió la FML por adición de SO_2. Letras superíndices diferentes señalan diferencias significativas entre los datos de la misma fila (ANOVA y prueba HSD de Tukey con n=2). Los datos sombreados corresponden a los datos de color obtenidos después de 48h del sulfitado de los vinos. Al momento del envasado, el contenido de SO_2 Total y Libre de los vinos estuvo por debajo de los límites establecidos por el INV

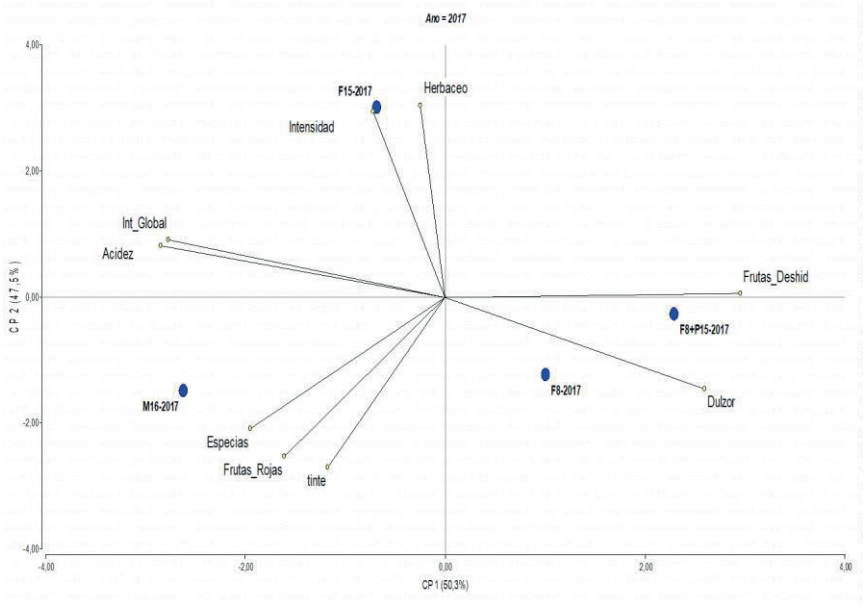

Figura 2: Análisis de componentes principales de los atributos sensoriales resultantes del análisis sensorial descriptivo de los vinos 2017. Intensidad: intensidad de color. Int_Global: intensidad global aroma; Frutas Rojas, Frutas Deshid (Deshidratadas) Especias, Herbáceo: notas aromáticas. Acidez y Dulzor, gusto. Las variables graficadas presentaron diferencias significativas (ANOVA $p<0,05$).

Las tablas 6 y 7 muestran los autovectores y las correlaciones de los componentes principales con las variables originales de la Figura 2.

Tabla 6: Autovectores Figura 2

Variables	e1	e2
Intensidad	-0,12	0,47
tinte	-0,19	-0,43
Int_Global	-0,44	0,15
Frutas_Rojas	-0,26	-0,40
Frutas_Deshid	0,47	0,01
Herbaceo	-0,04	0,48
Especias	-0,31	-0,33
Dulzor	0,41	-0,23
Acidez	-0,45	0,13

Tabla 7: Correlaciones con las variables originales Figura 2

Variables	**CP 1**	**CP 2**
Intensidad	-0,24	0,97
tinte	-0,40	-0,89
Int_Global	-0,94	0,30
Frutas_Rojas	-0,55	-0,83
Frutas_Deshid	1,00	0,02
Herbaceo	-0,08	1,00
Especias	-0,66	-0,69
Dulzor	0,88	-0,48
Acidez	-0,96	0,26

En relación al atributo color, en los vinos 2017 sin sulfitar los efectos de las cepas autóctonas Sc F8, y Sc M16, sobre el IC (índice de color) y la intensidad de color fueron similares a los descritos en la vendimia 2015 (efecto hipercrómico), aunque los vinos 2017 también mostraron un aumento de la absorbancia a 420nm (efecto hipsocrómico) que determinó un aumento significativo de sus tintes respecto del control (Sc F15) (Tabla 5). Por otra parte, el sulfitado de estos vinos derivó en una pérdida significativa de la intensidad de color la que fue más significativa en los vinos elaborados con las levaduras autóctonas (10-20%) que en la comercial (5%). En todos los vinos, la perdida de intensidad de color estuvo asociada a una significativa disminución de la absorbancia (aproximadamente 30%) a 520nm (dato no mostrado). Mientras 520nm es la $\lambda_{máx}$ de absorción de la antocianina mayoritaria de los vinos tintos, malvidina 3-glucósido sensible al SO_2, el resultado evidencia que la estabilización del color en los vinos jóvenes ocurre mediante la formación de copigmentos sensibles al SO_2 y que la hipercromía observada en los vinos elaborados con los cultivos puros de Sc autóctonos está relacionada con mayor contenido de estos pigmentos en sus vinos. Al igual que lo observado

en la vendimia 2015, la inclusión de P15 en el cultivo iniciador disminuyó significativamente la intensidad de color de los vinos. Adicionalmente, todos los vinos elaborados con los cultivos iniciadores autóctonos mostraron una menor pérdida del material colorante capaz de absorber luz a los 420nm (13%) que los elaborados con el cultivo comercial (20%) (datos no mostrados) y como consecuencia un aumento significativo en sus tintes (Tabla 5, datos sombreados). Aunque debe corroborarse experimentalmente, este resultado es consistente con el supuesto de un mayor contenido de pigmentos poliméricos de tipo A-T y/o piranoantocianinas [25]

Los pigmentos poliméricos y las piranoantocianinas, son pigmentos rojo anaranjados (absorben luz a λ<500nm, efecto hipsocrómico) resistentes a la decoloración por SO_2 que otorgan al color del vino el matiz rojo teja típico de los vinos añejados [29]. Existe evidencia que el acetaldehído, un metabolito secundario de las levaduras, acelera la formación de estos pigmentos antociánicos poliméricos, actuando de nexo de unión entre los antocianos y los taninos [25, 26], y que tanto el acetaldehído como el ácido pirúvico (otro metabolito fermentativo de las levaduras) intervienen en la formación de piranoantocianinas [25].

Al igual que en el 2015, el vino elaborado en la vendimia 2017 con el cultivo mixto autóctono Sc F8+P15 fue el preferido de los consumidores, aunque en esta oportunidad la preferencia estuvo compartida con el vino elaborado por el cultivo puro autóctono Sc F8 (Tabla 8).

Tabla 8: Prueba de Preferencia de Consumidores para los Vinos 2017 elaborados con la variedad Malbec y FAs conducidas por los cultivos iniciadores autóctonos puros (F8 y M16) y mixto (F8+P15) y por el comercial (F15)

Cultivo iniciador FA	Media	E.E	
F15	2,96	0,24	A
M16	2,69	0,23	A
F8	2,17	0,21	B
F8+P15	2,08	0,20	B

Medias con una letra común no son significativamente diferentes (p > 0,05), n=96

4. Conclusiones

La regularidad en la calidad fisicoquímica de los vinos elaborados durante las vendimias 2015 y 2017 pone en evidencia la estabilidad genética de las cepas de levaduras autóctonas de la Patagonia *S. cerevisiae* F8 y *P. kudriavzevii* P15, validando su aptitud

para ser usada en enología, en particular para vinificaciones tintas de la variedad Malbec.

Los cultivos iniciadores autóctonos Sc F8 y M16 impactan positivamente sobre la calidad sensorial de los vinos, intensificando significativamente su color, un atributo de preferencia al momento de la elección de un vino y que establece, junto con el contenido alcohólico, el valor comercial de éste.

Los cultivos iniciadores autóctonos puros y mixto potencian el aroma frutal y especiado de los vinos regionales, diferenciado positivamente su calidad y su preferencia por parte de los consumidores.

El cultivo autóctono mixto representa una herramienta alternativa a la FML para la deacidificación biológica de los vinos

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Evaluación de emulsiones filmogénicas a base de aislado de soja y cera de abeja

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Resumen. En el presente trabajo se estudiaron las propiedades de emulsiones de aislado proteico de soja, cera de abeja y glicerol (reología, estabilidad y distribución de tamaño de partícula). Además, se determinó la velocidad de transferencia al vapor de agua, espesor y propiedades mecánicas de las películas biodegradables obtenidas a partir de dichas emulsiones mediante el método de casting. Los resultados indicaron que la emulsión se corresponde con el comportamiento de un fluido no-newtoniano con un tamaño de gota promedio igual a 3,79 µ, siendo altamente estable durante el periodo de tiempo necesario para la fabricación de la película. Las películas obtenidas presentaron un espesor promedio igual a 148 µm y aquellas películas con cera presentaron menor velocidad de transmisión al vapor de agua, probablemente por las propiedades hidrofóbicas de este componente.

Keywords: Emulsión, aislado proteico de soja, cera de abeja.

1. Introducción

Una de las áreas de aplicación de las ceras de abeja, y que en la actualidad se investiga intensamente, es el campo de las películas y recubrimientos comestibles. Una película comestible es una capa delgada y continua, hecha de materiales que pueden ser ingeridos por el consumidor, y que proveen una barrera contra la humedad, oxígeno y otros solutos [1]. Para conseguir una funcionalidad óptima de los recubrimientos, es especialmente importante la selección de los materiales que los forman, ya que sus propiedades están fuertemente afectadas por la naturaleza de sus componentes, composición y estructura final. Parámetros como distribución de tamaño de partículas, estabilidad, interacción de sus componentes, entre otros, determinan la estructura de las emulsiones filmogénica y afectan notablemente a las propiedades de los films resultantes.

Muchas biomoléculas, incluyendo proteínas, carbohidratos y lípidos han sido ampliamente utilizados para la elaboración de films comestibles. Las proteínas de soja son uno de los materiales mayormente utilizando debido a que presenta una excelente capacidad de producir films comestibles [2]. La combinación de proteínas de soja con lípidos y mezclas de lípidos es una alternativa interesante para optimizar las propiedades del film, debido a que algunos componentes tal como el ácido oleico brinda flexibilidad a través de sus propiedades plastificantes, mientras que otros como las ceras

de abeja pueden mejorar la eficiencia de los films como barreras a la permeabilidad del vapor de agua [3].

Sobre esta base en el trabajo realizado se planteó el estudio de emulsiones filmogénicas a base de aislado proteico de soja y cera de abeja.

2. Materiales y métodos

2.1. Elaboración de emulsiones

Se prepararon formulaciones en base a aislado proteico de soja (P) (90.8% proteínas, 6.58% humedad, 0.5% grasas, 5% cenizas), glicerol (G) (Anedra, pureza: 98-99%, reactivo grado analítico), ceras de abeja (W) y ácido oleico (AO). La cera de abeja fue provista por Ceras Argentinas S.R.L. (Buenos Aires, Pigüé). Antes de su uso, la misma fue purificada mediante extracción Soxhlet utilizando hexano como solvente.

Las emulsiones formuladas presentaron una relación proteína:lípidos de 1:0,50 y 1:0,75, distribuidos como G:W:AO 1:0,5:0 (PGW-0,75) y 1:1,6:0 (PGW-0,5), G:W:AO 0,33:0,33:0,33 (PGW-AO) y G:W:AO 1:0:0 (PG).

Las emulsiones fueron preparadas mediante la hidratación de la cantidad necesaria de proteína de soja en agua destilada a temperatura ambiente y posteriormente el pH fue llevado a 10 utilizando NaOH 1 M. La solución fue calentada a 90 °C en un baño de agua con agitación constante durante 30 minutos hasta lograr la disolución completa; luego se adicionó el glicerol como agente plastificante [4, 5]. Para obtener las formulaciones PGW-0,5 y PGW-0,75 las ceras de abeja (W) fueron añadidas a la mezcla y luego homogeneizada utilizando un mixer de mano (14500 rpm) durante tres ciclos de 30 segundos cada uno, transfiriéndola inmediatamente a un baño de hielo con agitación. Finalmente, la emulsión obtenida fue filtrada con un paño de gasa para eliminar la espuma residual acumulada en la superficie. El mismo procedimiento fue realizado para obtener PGW-AO, incorporando AO para evaluar el efecto del agregado de otro componente lipídico, y PG, sin incorporar lípidos a la fórmula.

2.2. Caracterización de emulsiones

2.2.1. Distribución de tamaño de gotas.

El tamaño de partícula y la distribución del tamaño fueron caracterizado mediante un láser de dispersión Horiba LA-910 analizador de tamaño de partículas (Horiba Ltd., Kioto, Japón). El tamaño de partícula fue calculado por el analizador basado en el valor medio de la longitud geométrica de las partículas medido a través de diferentes orientaciones de dispersión incidencia de luz.

2.2.2. Propiedades reológicas.

El análisis del comportamiento reológico se realizó utilizando un reómetro Paar Physica (modelo MCR 301, Anton Paar GmbH, Austria) con una geometría de conos (diámetro 50 mm) y un sistema de adquisición de datos computarizado (Rheoplus / 32 V3.40). La emulsión se colocó sobre la base inferior de la geometría y la prueba de barrido de velocidad de cizallamiento ($\dot{\gamma}$) se realizó a 20 °C variando este parámetro entre 0.1 y 100 1/s. Los datos experimentales se ajustaron de acuerdo a la ley de la potencia para fluidos no newtonianos de acuerdo a la siguiente ecuación:

$$\tau = K\dot{\gamma}^n \quad (1)$$

Donde K es el índice de consistencia (Pa s^n), n el índice de comportamiento de flujo (adimensional) y τ el esfuerzo de corte (Pa s).

2.2.3. Estabilidad.

La estabilidad de las emulsiones se determinó utilizando un analizador macroscópico de barrido vertical, Turbiscan (TurbiScan MA 2000, Toulouse, France). Aproximadamente 7 mL de cada emulsión fueron colocados en tubos de vidrio, el porcentaje de cambio en backscattering (ΔBS%) fue medido aproximadamente cada 20 minutos durante la primera hora. luego cada una hora y luego de manera más espaciada durante al menos 25 horas. La formulación PGW-0,5 fue monitoreada a tiempos superiores para evaluar su estabilidad en un tiempo más prolongado. Las emulsiones en estudio fueron opacas, por lo que sólo los perfiles backscattering se utilizaron para evaluar la estabilidad físico-química de las emulsiones.

2.3. Elaboración de películas

Las biopelículas fueron elaboradas mediante el método de casting utilizando placas de Petri de 10 cm de diámetro y moldes rectangulares de 5x12 cm empleando papel film de plástico para alimentos como superficie de contacto. Aproximadamente 18 y 16 g de la cada formulación fueron vertidos en cada placa circular y rectangular, respectivamente. Se realizaron 3 réplicas de cada placa. Las mismas se dejaron secar en una estufa con flujo de aire convectivo a 40 °C durante aproximadamente 24 h. Cuando se logra la evaporación del agua, una película fina de proteínas, o de proteína y lípidos queda depositada sobre la superficie de la placa. Las películas se extrajeron de las placas y se acondicionaron en ambientes de humedad relativa conocida (NaBr 0,577% HR) a 25 °C antes de las determinaciones pertinentes.

2.4. Caracterización de películas

2.4.1. Espesor

El espesor de los films se determinó utilizando un micrómetro manual con una precisión de 5 µm. Se realizaron cinco mediciones sobre cada película, cuatro en el perímetro y una central. Se tomó el promedio como valor del espesor en los cálculos de permeabilidad.

2.4.2. Velocidad de transferencia al vapor de agua.

La velocidad de transmisión al vapor de agua (VTVA) se determinó de acuerdo a la norma E 96-00 [6]. Para ello se utilizó una cámara de permeación con agua en su interior. La tapa superior de la cámara presenta un orificio, el cual fue sellado por la película en estudio. A su vez, dicha cámara se colocó dentro de un desecador en presencia de una atmósfera a aproximadamente 50% HR, la cual se logró empleando una solución saturada de nitrato de calcio tetrahidrato (Anedra, grado analítico). Las celdas de permeación se pesaron diariamente para registrar la cantidad de agua que permeó a través de la película, y abandonó la celda. Al finalizar el ensayo se realizó una regresión lineal entre los pesajes de la celda y el tiempo transcurrido. La VTVA (g/ s m^2) se calculó como la pendiente de dicha regresión sobre el área expuesta de la película. La determinación se realizó por duplicado.

2.4.3. Propiedades mecánicas.

Las propiedades mecánicas de determinaron mediante el método S 882 [7]. Las mismas incluyen el porcentaje de elongación (E%), tensión de rotura (TS) y el módulo elástico o módulo de Young (Y). Los ensayos se realizaron empleando un texturómetro TA-Plus (Lloyds Instruments, UK). El tamaño de la muestra fue un rectángulo de 12 cm de largo y 2.5 cm de ancho. La muestra es estirada longitudinalmente, a velocidad constante (20 mm/min), mediante dos grampas que sujetan los extremos de la misma. El ensayo finaliza una vez que la muestra cede ante la fuerza y se rompe. La separación inicial entre las grampas fue igual a 9 cm. Los ensayos fueron realizados por triplicado.

3. Resultados y discusión

3.1. Caracterización de emulsiones.

Tamaño de gota. La Figura 1 muestra la frecuencia del tamaño de partículas de las diferentes emulsiones Se puede observar tamaños de gotas esperables para el modo en que se realizó la homogenización (~2,0 µm) [8] Si bien las emulsiones PGW-AO tuvieron el tamaño de gotas más pequeñas (moda:2,114 ± 0,001), no difieren notablemente de la emulsión PGW-0,75 (moda: 2,779 ± 0,002). El incremento en el contenido de lípidos no afectó la distribución final de las partículas en las emulsiones.

La incorporación de AO redujo el tamaño de gota durante el proceso de emulsificación. Esto puede justificarse por la naturaleza hidrofílica del AO que facilita las interacciones polares con la proteína incrementando la dispersión [9]

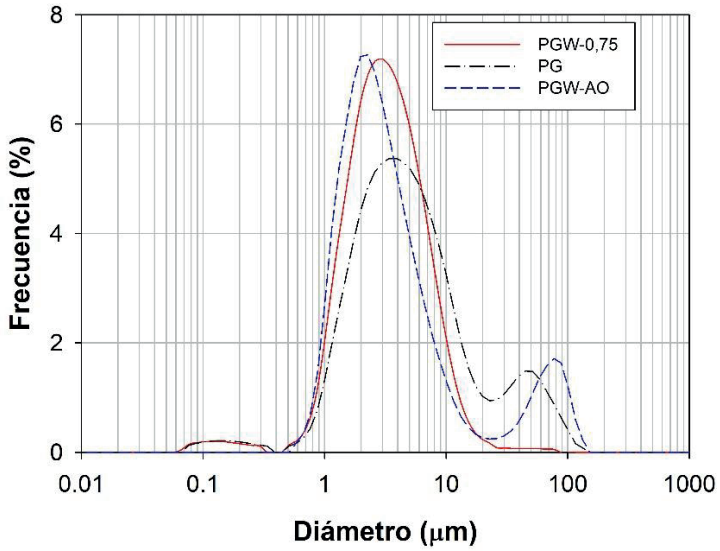

Fig. 1. Distribución de tamaño de gota de las emulsiones PGW-0,75, PG y PGW-AO

Reología. El análisis reológico de las emulsiones se muestra en la Fig. 2 Todas las emulsiones tuvieron un comportamiento pseudoplástico. Los índices de flujo para las emulsiones PGW-AO, PGW-0,5 y PGW-0,75 fueron 0,93, 0,89 y 0,96 respectivamente. Estudio similar de emulsiones con caseinato de sodio con AO y cera de abeja arrojó comportamiento Newtoniano excepto con el agregado de ácido esteárico (índice de flujo 0,79). Si comparamos las emulsiones con una relación de proteínas:lípidos 1:0,5, podemos observar las emulsiones con AO poseen una mayor viscosidad debido a un menor tamaño de partículas y a una mayor interacción entre lípidos-proteína. Comportamiento similar se registró para emulsiones caseinato de sodio-cera de abeja-ácido oleico [9]. Por otra parte, la emulsión con mayor cantidad de ceras (PGW-0,75 y PGW-0,5) presentó menor viscosidad y esto podría explicarse porque su incorporación de dejaría más solvente libre en el sistema [9].

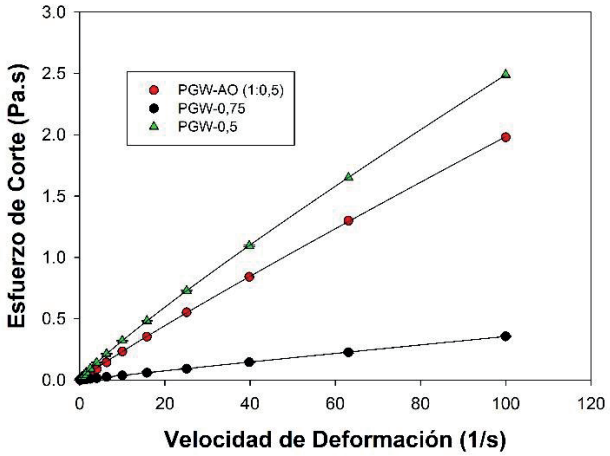

Fig. 2. Comportamiento reológico de las emulsiones PGW-0,75, PGW-0,5 y PGW-AO

Estabilidad. En la Figura 3 se observan las emulsiones colocadas en los tubos que luego fueron analizados en el TurbiScan. Las mismas exhibieron un color blanquecino. Los perfiles de transmisión no se presentan, ya que las emulsiones son opacas y no permiten el paso de la luz, haciendo que los valores de Transmission sean 0%.



Fig. 3. Tubos de ensayo con las emulsiones para ser analizadas mediante el equipo TurbiScan MA 2000.

En la Figura 4 se observan los perfiles de backscattering de las diferentes emulsiones elaboradas. En la figura 4-a se observa el perfil obtenido para la emulsión PG, en el fondo del tubo se produjo un desplazamiento hacia arriba de los perfiles, inicio del proceso de sedimentación, mientras que el en centro del tubo permanecen iguales. La Figura 4-b corresponde a las emulsiones PGW-0,5, se observa que el agregado de ceras provoca en el fondo del tubo un desplazamiento de los perfiles hacia abajo, indicando que se presenta el proceso de cremado. En el centro del tubo los perfiles comienzan a desplazarse hacia abajo, indicando un aumento del tamaño de las partículas. La figura 4-c corresponde a las emulsiones PGW-AO, en el fondo del tubo se observa que los perfiles se desplazan hacia arriba inicialmente, presentando el mismo comportamiento

que las emulsiones PG, sin embargo, a las 23 horas de medición el perfil presenta un desplazamiento hacia abajo, comenzando el proceso de cremado. El agregado de AO a la emulsión provoca que el inicio del proceso de cremado se vea retrasado, con respecto a la emulsión sin agregado de AO.

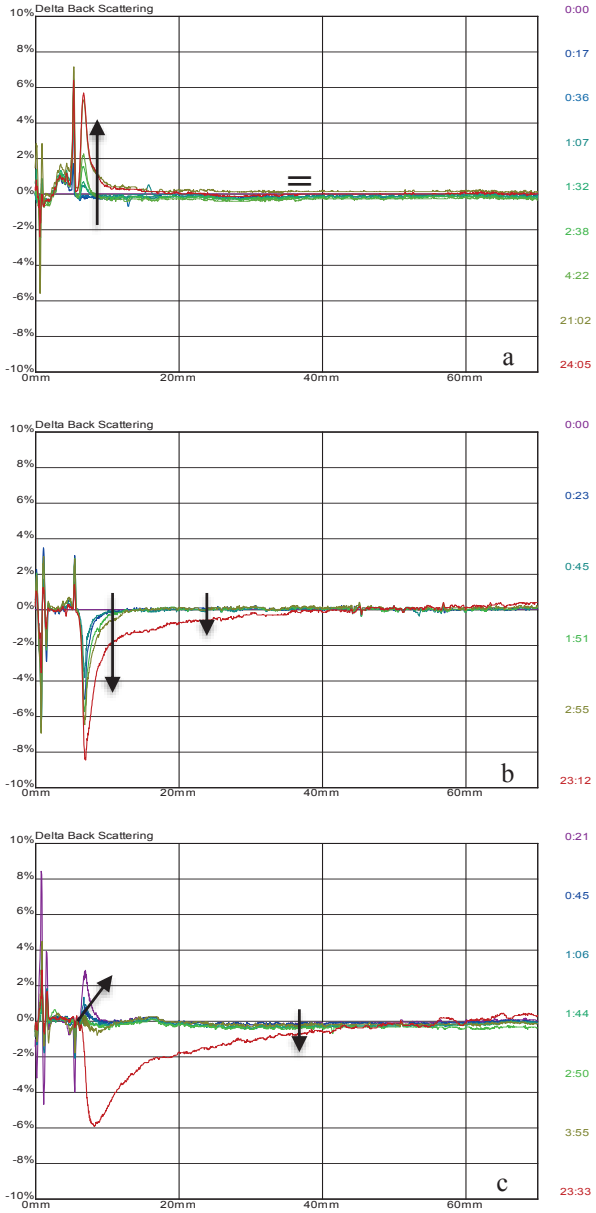

Fig. 4. Datos de backscattering de las emulsiones elaboradas, a) PG, b) PGW-0,5, c) PGW-AO, TurbiScan MA 2000.

Al no observarse alteraciones importantes puede afirmarse que las emulsiones formadas en todos los casos fueron estables en el tiempo considerado necesario para la elaboración de los films (24 horas).

En la Figura 5 se observan los perfiles de backscattering de emulsiones elaboradas con diferente relación lípido/proteína (PGW-0,5 y PGW-0,75). En ambas puede observarse un desplazamiento hacia debajo de los perfiles en el fondo del tubo, sin embargo, cuando la proporción de lípidos fue mayor (Fig 5-b), el desplazamiento fue mayor, indicando que el aumento del contenido de lípidos en la emulsión promueve los procesos de desestabilización.

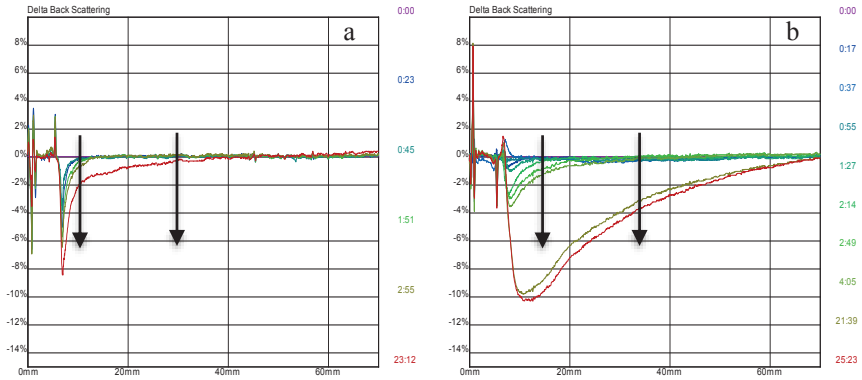

Fig. 5. Datos de backscattering de las emulsiones elaboradas con diferente relación lípidos/proteína, a) PGW-0,5, b) PGW-0,75, TurbiScan MA 2000.

Con el objetivo de evaluar la estabilidad de las emulsiones a tiempos superiores la formulación PGW-0,5 fue monitoreada durante aproximadamente 20 días, en la Figura 6 se presentan los perfiles de backscattering obtenidos. Puede observarse que la señal de BS% en el centro de los tubos presenta una disminución a lo largo del tiempo, indicando que hay un aumento del tamaño de partículas. También se observa que la señal en el fondo del tubo aumenta y mientras que en el tope disminuye, indicando que ocurren procesos de sedimentación.

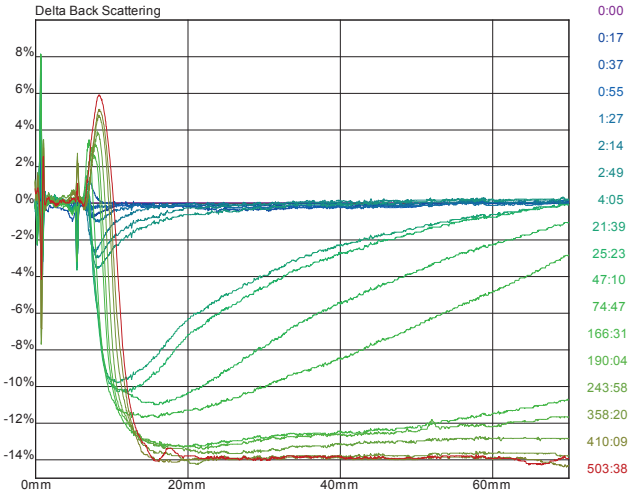

Fig. 6. Datos de backscattering de emulsiones elaboradas PGW-0,5 medidas a tiempos superiores, TurbiScan MA 2000.

3.2. Caracterización de películas.

En la Figura 7 se presentan imágenes de los films obtenidos a partir de las diferentes formulaciones elaboradas. En las fotografías puede observarse que todas las películas fueron opacas, y que el agregado de ceras y de AO no provocaron cambios en su apariencia. Las películas obtenidas con las emulsiones más concentradas en ceras fueron rugosas y no uniformes, y las películas obtenidas utilizando ceras y AO (PGW-AO) fueron frágiles y difíciles de manipular. Debido a esto solo pudieron ser analizadas las propiedades de los films elaborados con las formulaciones PG y PGW-0,5.

El espesor promedio de las películas obtenidas fue 148 ± 9 µm. La VTVA correspondiente a la película obtenida con la formulación PGW-0,5 fue 7.981 ± 0.001 g/ s m^2, mientras que para la película obtenida a partir de PG se obtuvo un valor de 9.47 ± 0.001 g/ s m^2, siendo esta última significativamente superior a la primera ($p<0.05$). Esto indica que las ceras aportan hidrofobicidad al film ayudando a retener la humedad del lado interno del film.

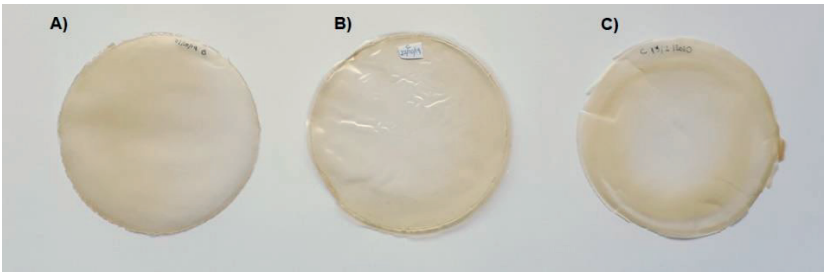

Fig. 7. Imágenes de los films obtenidos con las emulsiones: A) PGW-0,5, B) PG y C) PGW-AO.

La Tabla 1 muestra las propiedades mecánicas de las películas con y sin cera (PGW y PG). Se puede observar que tanto el parámetro TS como E% fueron significativamente mayores para el film sin cera indicando que la adición de cera produce una reducción en la elasticidad del film y requiriendo una menor fuerza para alcanzar la ruptura del mismo. La deseabilidad de algún valor predeterminado de alguna de estas propiedades dependerá exclusivamente de la aplicación específica de la película.

Table 1. Propiedades mecánicas promedio de las películas PGW y PG: porcentaje de elongación (E%), tensión de rotura (TS) y el módulo elástico o módulo de Young (Y).

	PGW	PG
TS (MPa)	$0.827^{a} \pm 0.183$	$1.282^{b} \pm 0.191$
E%	$6.11^{a} \pm 0.74$	$59.15^{b} \pm 19.72$
Y (MPa)	$17.92^{a} \pm 1.28$	$21.27^{a} \pm 2.44$

Subíndices con letras diferentes dentro de una misma fila indican diferencias significativas ($p<0.05$).

4. Conclusiones

En el presente trabajo se analizaron las propiedades de emulsiones compuestas de aislado proteico de soja, cera de abeja y glicerol, como también de las películas biodegradables obtenidas con las mismas. Como conclusiones generales se puede mencionar que las emulsiones resultaron altamente estables dentro del período de tiempo necesario para fabricar los films. Además, se observó que el agregado de las ceras produjo una disminución en la velocidad de transmisión al vapor de agua, probablemente causado por las propiedades hidrofóbicas de las mismas. Estos resultados los resultados alientan a profundizar las investigaciones sobre este tipo de emulsiones, con el objetivo de elaborar películas comestibles.

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Caracterización de propóleos como fuente lipídica con compuestos activos

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Resumen. El presente trabajo se centra en la caracterizaron de un total de veintiséis (26) muestras de propóleos crudos provenientes de diferentes localidades de la provincia de Buenos Aires y Valle de Río Negro y Río Colorado cosechados mediante los métodos de malla y raspado. La fracción de cérea contenida en el propóleos actualmente representa un residuo de la industria apícola que podría presentar compuestos bioactivos de interés, por lo que también fue parcialmente caracterizada. En general, los resultados indicaron que todos los propóleos cumplen con los requisitos impuestos por el Código Alimentario Argentino. Se determinó que el método de cosecha (malla o raspado) afecta la composición del propóleo en cuanto a su contenido de ceras y resinas. El contenido de compuestos fenólicos de los propóleos estuvo en un rango entre 1,5 y 2,9 % (p/p). El contenido de ceras de los propóleos analizados varió entre 12,3-48,9 % (b.s.), y se determinó que aproximadamente el 30% de los compuestos fenólicos presentes en el propóleo original son retenidos por las ceras. Estos resultados alientan la investigación del potencial uso de las ceras de propóleos en aplicaciones comerciales, como podrían ser el desarrollo películas biodegradables con contenidos de componentes bioactivos para el recubrimiento de alimentos.

Palabras clave: Propóleos, ceras de propóleos, método de cosecha, caracterización.

1 Introducción

El propóleos es un producto apícola que se compone mayormente de resinas que las abejas colectan de diferentes plantas, procesándolas y mezclándolas con su propia cera, para luego utilizarlo como protección de la colmena frente a diversos agentes patógenos. La fracción resinosa de este producto apícola es extraída y utilizada en la produc-

ción de múltiples formulaciones alimenticias debido al elevado contenido de compuestos bioactivos con efectos antimicrobianos y antioxidantes [1], siendo la fracción cérea desechada. Además, los estándares de aceptabilidad para el procesamiento de propóleos requieren un contenido de cera inferior al 40% [2], descartando aquellos propóleos que no cumplen con dicha especificación. En base a esto, el objetivo principal de este trabajo se centró en la caracterización de las ceras extraídas de propóleos provenientes de diferentes localidades bonaerense, valle del Río Negro y valle del Río Colorado, obtenidas por el método de raspado y malla, con el objetivo de evaluar su aplicación en diversas formulaciones alimentarias.

2 Materiales y métodos

Se estudiaron veintiséis (26) muestras de propóleos cosechadas entre los años 2016-2020, dieciséis de ellas recolectadas por el método de malla y las restantes por el método de raspado. Se establecieron cinco sitios de muestreo: valle inferior del Río Negro (muestras de Patagones y Viedma), valle bonaerense del Río Colorado (muestras de Villalonga, Pedro Luro e Hilario Ascasubi), la cuenca del Río Salado (muestras de Rauch) y la costa atlántica (muestras de Villa Gesell).
La caracterización del propóleos se realizó de acuerdo a la norma IRAM-INTA-15935 del Instituto Argentino de Normalización y Certificación. Se determinaron contenido de resinas [3], humedad, impurezas mecánicas, cenizas [4] y contenido de ceras.

Las ceras extrajeron con *n*-hexano mediante equipo Soxhlet [3]. Todas las determinaciones se realizaron por duplicado y se expresaron en % base seca (bs) de propóleos.

El color del propóleos crudo molido fue determinado mediante los parámetros de color CIELAB en un colorímetro Hunterlab a 25 ºC.
El análisis cualitativo de las ceras se realizó por comatografía TLC, utilizando una mezcla solvente de hexano, dietil éter y ácido acético en una relación 85:15:2, respectivamente y atmósfera de iodo como revelador. Se utilizaron como estándares [8]: alcoholes, hidrocarburos, ácido oleico, metil ésteres de ácidos grasos y colesterol. Se analizaron dos muestras de cera pertenecientes a propóleos con diferente método de cosecha (raspado y malla).

El punto de fusión de las ceras se determinó mediante calorimetría diferencial de barrido en un calorímetro Q20 TA Instrument. El rango de temperatura analizado fue 25-80 °C a una velocidad de 5°C/min.

Los compuestos fenólicos de las muestras de propóleos y ceras fueron extraídos en sistema agitado con metanol a temperatura ambiente por 24 h. El contenido de fenoles totales en el propóleo crudo y la cera recuperada fue determinado empleando el método de Folin-Ciocalteu (λ=765 nm, ácido gálico como estándar) y los flavonoides totales se determinaron en la cera mediante el método espectrofotométrico (λ=425 nm) empleando $AlCl_3$ [6, 7] y quercetina como estándar.

Los resultados se analizaron aplicando técnicas estadísticas de comparación de medias (prueba t de Student) con un nivel de significancia del 95% y análisis de varianza (ANOVA).

3 Resultados y discusión

En relación a lo establecido por el Código Alimentario Argentino [2], el contenido de humedad se encuentra por debajo del máximo establecido por dicho organismo (11% bs). El contenido de cenizas excedió el máximo permitido en solo dos muestras y el máximo registrado corresponde a propóleos recolectado en la localidad de Pedro Luro mediante el método de mallas (13,1%, bs). Solo tres muestras superaron levemente el contenido máximo de cera permitido por el CAA (40%). Todas las muestras presentaron un contenido de resinas (30%) y de fenoles totales (mínimo 5%) superior al mínimo establecido por el CCA.

En comparación con fuentes bibliográficas que reportan la caracterización de propóleos de la provincia de Buenos Aires [3], se puede mencionar que todos los parámetros reportados son similares a excepción del contenido de fenoles, el cual fue aproximadamente la mitad que el reportado por otros autores (22%). En general, se podría decir que la caracterización del propóleos de la provincia de Buenos Aires se ha mantenido relativamente constante a través del paso de los años.

En relación al color, la luminosidad (L) promedio de las muestras fue 53 ± 5. Considerando que el CV% fue inferior al 10% se podría decir que es un valor representativo para todo el conjunto de muestreo. Por otro lado, los parámetros a* y b* presentaron coeficientes de variación del 30 y 17%. A pesar de esto, todos los propóleos mostraron una coloración combinada entre rojo (valores positivos del parámetro a*) y amarillo (valores positivos del parámetro b*). Al agrupar las muestras de acuerdo al método de recolección, aquellas obtenidas mediante malla presentaron un valor de L y b* superior a aquellas correspondientes al método de raspado ($p<0.02$). Esto indica que los propóleos provenientes de mallas son levemente más luminosos y de un color amarillo más intenso. No se encontraron diferencias significativas en relación al parámetro a* ($p>0.07$).

Un parámetro importante que determina la calidad del propóleos es el contenido de resinas en relación al contenido de ceras, ya que la resina es la fracción del propóleos que contiene los compuestos bioactivos beneficiosos para la salud [9]. Por este motivo, se realizó la comparación entre las muestras recolectadas mediante el método de malla y raspado. Los resultados mostraron que el propóleos obtenido mediante el método de recolección por raspado presentó una mayor relación entre estos componentes ($p<0.05$).

El punto de fusión promedio de la cera de propóleos fue 61,3 ± 0,9 °C. Al comparar grupos de muestras provenientes de diferentes métodos de recolección, aquellas provenientes de mallas presentaron su punto de fusión 1 °C mayor que las de raspado ($p<0.04$).

El contenido máximo de fenoles en la cera de propóleo fue 2,9% (bs), mientras que el mínimo fue 1,5%. Si se utiliza el contenido de cera y fenoles promedio de las muestras, es posible determinar que aproximadamente el 30% de los compuestos fenólicos presentes en el propóleo crudo quedaron retenidos en la fracción de cera. Este resultado es de importancia ya que incentiva el desarrollo de nuevas aplicaciones para este residuo de la industria apícola. Además, al comparar muestras obtenidas mediante diferentes métodos de recolección, aquellas correspondientes al método de malla (2,4 ± 0,4% bs) presentaron un promedio significativamente mayor a las de raspado

(1,9 ± 0,3%, bs). Por último, las ceras presentaron un contenido de flavonoides entre 0.30 y 0.64% (bs).

El análisis cualitativo por TLC arrojo que las ceras contienen todos los compuestos de referencia: hidrocarburos, ésteres de ácidos grasos, alcoholes y colesterol [10].

4 Conclusiones

En el presente trabajo se realizó la caracterización de propóleos proveniente de diferentes regiones de la provincia de Buenos Aires, Valle del Río Negro y Valle del Río Colorado, así como también la fracción cérea presente en el mismo. Si bien en general todas las muestras respetan las normativas establecidas por el Código Alimentario Argentino, se encontró que la proporción de resina:cera es diferente de acuerdo al método de cosecha implementado, siendo la misma superior en los propóleos recolectados mediante el método de raspado. Además, se detectó que aproximadamente el 30% de los compuestos fenólicos presentes en el propóleo crudo quedan retenidos en la fracción cérea. Estos resultados alientan el estudio de las posibles aplicaciones para este residuo de la industria apícola.

5 Referencias

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Afinidad del caseinomacropéptido con el $CaCl_2$ a pH neutro

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Resumen. El complejamiento del calcio con péptidos y su impacto en la biodisponibilidad de este mineral tiene mucha vigencia. El calcio es un mineral esencial para la correcta salud ósea, pero su absorción en el intestino es baja debido a la formación de sales insolubles. Por otro lado, el caseinomacropéptido (CMP) es un péptido con propiedades bioactivas obtenido de la hidrólisis enzimática específica de la κ-caseína por acción de la pepsina o quimosina durante la elaboración del queso. Para incrementar la ingesta y bioaccesibilidad del calcio en la población es importante analizar tanto la afinidad como el modo de interacción del CMP por el calcio. Se evaluó, el efecto de la incorporación de $CaCl_2$ sobre la asociación molecular del CMP mediante la técnica de dispersión dinámica de luz láser. Adicionalmente, se analizaron los espectros infrarrojos con transformadas de Fourier. Las modificaciones observadas en los espectros de CMP y $CaCl_2$ a pH neutro confirmaron que el CMP interacciona con el calcio a través de los residuos carboxílicos que corresponderían al Asp y Glu. Los cambios en la zona de amidas indicaron cambios en la estructura secundaria del péptido. Por otro lado, los resultados de DLS mostraron la formación de estructuras asociadas por pares de moléculas de CMP (dímeros, tetrámeros, hexámeros) en presencia de $CaCl_2$, alcanzando un grado máximo de asociación, el hexámero, para la relación 1,2 mmol $CaCl_2$/g de CMP. Dada la potencialidad del CMP como péptido ligante, este trabajo plantea un nuevo ingrediente funcional con alto valor agregado.

Palabras clave: caseinomacropéptido, $CaCl_2$, DLS, FTIR, interacción

1 Introducción

El Caseinomacropéptido (CMP) es un péptido de origen animal, que proviene del suero de queso luego de la escisión de la κ-caseína por vía enzimática y posee numerosas

propiedades bioactivas. El CMP es afectado por el pH ya que contiene dos residuos de Asp, siete u ocho de Glu (dependiendo de la variante B o A del CMP, respectivamente), una Ser fosforilada y tres residuos de Lys. A pH 7,0 y en ausencia de sales, tiene una fuerte carga negativa siendo su ξ de -24,12 mV [1]. Teniendo en cuenta sus propiedades funcionales y sus características bioactivas, resulta de gran interés su estudio para el desarrollo de nuevos ingredientes funcionales, especialmente caracterizar si el CMP presenta cierta capacidad ligante de calcio. Para incrementar la ingesta y bioaccesibilidad del calcio en la población es importante analizar tanto la afinidad como el modo de interacción del CMP por el calcio. A diferencia de otros péptidos, el CMP se destaca también por su abundancia como subproducto de la quesería. La interacción entre el CMP y el calcio puede observarse a nivel molecular. Sin interacción entre el CMP y el calcio se esperaría que los tamaños de partícula característicos para el CMP se mantengan y, al contrario, un cambio en el tamaño sería indicativo de una interacción molecular. Esta metodología se ha utilizado con este fin en diferentes trabajos [2-6]. El objetivo de este trabajo fue caracterizar a nivel molecular las interacciones entre el CMP y el $CaCl_2$ en solución a pH neutro. Se evaluó en primer lugar, el efecto de la incorporación de $CaCl_2$ sobre la asociación molecular del CMP mediante la técnica de dispersión dinámica de luz láser (DLS, en inglés). Adicionalmente, se analizaron los espectros infrarrojos con transformadas de Fourier (FTIR). Esta técnica es especialmente útil para el estudio de compuestos orgánicos ya que la abundancia de bandas de absorción específicas garantiza poder identificar compuestos puros o modificaciones. A través de esta técnica se pueden observar modificaciones a nivel molecular e identificar cuáles son los grupos funcionales que intervienen en las interacciones.

2 Materiales y métodos

2.1 Materiales

Se utilizó caseinomacropéptido BioPURE-GMP® de Davisco Foods International (USA). Su pureza, según el proveedor, fue (en base seca): 90,0 ± 3,0% (p/p) de CMP (N x 7,07). Su contenido mineral fue (100 g de muestra): 950 mg de Na; 125 mg de K y 682 mg de Ca determinados mediante espectrometría de absorción atómica Analyst 200 Perkin Elmer (USA). Se utilizó $CaCl_2$ anhidro (Merck, Alemania) de calidad analítica. El agua utilizada para preparar las soluciones fue ultrapura (Thermo Scientific Barnstead, modelo Easypure RF) y su conductividad fue 1,8 ± 0,1 μS/cm.

2.2 Métodos

2.2.1. *Preparación de las soluciones.* Se utilizaron concentraciones de CMP del 1 y 5% (p/p). Las soluciones de CMP se prepararon como en Loria et al. [7] hasta alcanzar la concentración de sal deseada (entre 0 y 250 mM) de $CaCl_2$. El CMP es muy soluble en agua y no se formó ningún precipitado después de añadir las soluciones salinas. El pH se ajustó a 7,0 con NaOH (c).

2.2.2 *Dispersión Dinámica de Luz (DLS).* Las mediciones de tamaño de partícula fueron realizadas en un equipo de DLS Zetasizer Nano–Zs de Malvern Instruments (Malvern, Inglaterra) provisto de un láser He–Ne (633 nm) y un correlador digital, modelo ZEN3600 según la técnica descrita en [8]. Las mediciones fueron realizadas a un ángulo fijo de dispersión de 173º. El rango de medición del equipo es 0,6–6000 nm. Los ensayos fueron realizados por triplicado y a temperatura ambiente. Las muestras fueron previamente filtradas a través de microfiltros Whatman International Ltd. (Maidstone, Inglaterra) de 0,45, 0,22 y 0,02 μm.

2.2.3. *Espectroscopía FTIR*. Las muestras en solución fueron almacenadas en freezer a una temperatura de -80ºC durante 24 hs y posteriormente liofilizadas (Labconco® freezone 12). Los espectros fueron registrados a temperatura ambiente en un espectrofotómetro infrarrojo Shimadzu® (modelo IR Prestige-21, Japón) en un rango de longitud de onda de 4000 nm^{-1} a 500 nm^{-1}. Se utilizó 1 mg de muestra liofilizada mezclada con 100 mg de KBr, pulverizada en un mortero de ágata y luego presionada a 20 Bar para obtener una pastilla. Cada muestra se sometió a 40 scans con 2,0 cm^{-1} de resolución. El registro de datos se realizó con el software LabSolution IR®, y el análisis de los espectros y los picos con el software OriginPro® 8 SR0, V8.0724, USA.

2.2.4. *Análisis estadístico.* Se utilizó el software GraphPad Prims v7.0 (GraphPad Software, San Diego, CA, USA) para el análisis estadístico. Los datos fueron analizados a través de un análisis de varianza (ANOVA). Las diferencias fueron determinadas por la prueba de Tukey para $P < 0,05$.

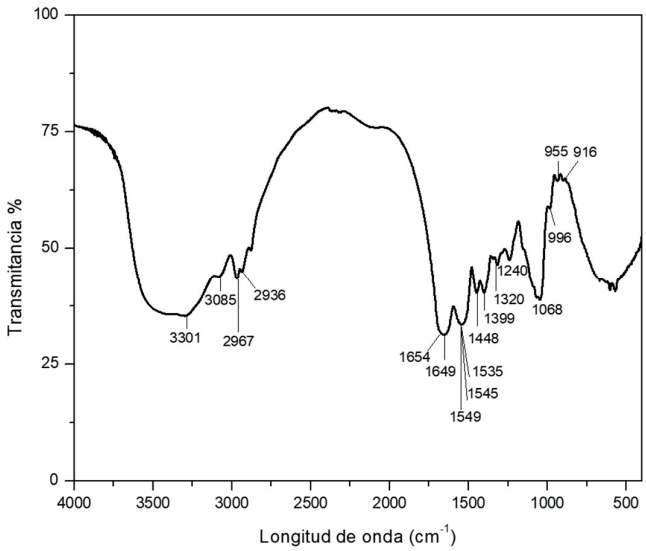

Fig. 1 Espectro FTIR del CMP a pH 7.

Tabla 1 Asignación de picos en los espectros FTIR del CMP en ausencia de sales y con 1,2 mmoles de $CaCl_2$/g CMP a pH 7,0. Se marcan en negrita las discrepancias con respecto al espectro de CMP sin sales.

Región		**Longitud de onda de CMP (cm^{-1})**	**Longitud de onda de CMP/$CaCl_2$ (cm^{-1})**
Grupos Funcionales (4000-1300 cm^{-1})	Amida 2° A (3300 cm^{-1})	3301	**3283**
	Amida 2° B (3080 cm^{-1})	3080	**3088**
	Amida I (1700-1600 cm^{-1})	1649	1650
		1655	1656
	Amida II (1600-1500 cm^{-1})	1535	-
		1545	-
		1549	1548
	Amida III (1240 cm^{-1})	1239	1241
	CH_3- (2970 cm^{-1})	2967	2968
	CH_3- (2940 cm^{-1})	2936	2937
			2945
	CH_2- (1450 cm^{-1})	1448	1447
	COO^- (1400 cm^{-1})	1400	**1416**
	Aminas CO-N (1320 cm^{-1})	1317	1319
Huella digital (1300-400 cm^{-1})	Residuos glicosilados (1075 cm^{-1})	1076	1077
	P-O (990 cm^{-1})	984	**997**
		901	901
	Picos de baja intensidad (900-935 cm^{-1})	916	**921**
		935	**940**

Las asignaciones del espectro fueron adaptadas de Wang et al. [9]

3 Resultados y discusión

3.1. Espectro FTIR del CMP a pH neutro.

El espectro FTIR del caseinomacropéptido (Fig. 1) fue similar al obtenido por Burgardt et al. [10], quienes utilizaron un material del mismo proveedor. En un espectro FTIR se distinguen principalmente dos zonas: una región de huella digital o fingerprint (1300 - 600 cm^{-1}) y otra región correspondiente a los grupos funcionales (4000 - 1300 cm^{-1}). Esta última región da información para identificar el tipo y carga de los grupos, mientras que la región de la huella digital indica las características estructurales de la molécula [9]. Las asignaciones se muestran en la Tabla 1.

En el espectro de la Fig. 1 se puede observar una banda ancha e intensa entre 3400 y 3300 cm^{-1}. Se debe a un solapamiento de bandas correspondientes a la vibración de los estiramientos O–H, libre o unido [10]. Las absorciones de tensión N-H tienen lugar a frecuencias ligeramente más bajas que las absorciones de tensión del O-H. Las bandas de las amidas secundarias A y B se encuentran a 3300 cm^{-1} y 3080 cm^{-1}, respectivamente [10]. La banda de la amida A corresponde al estiramiento del enlace N–H en la formación de la unión puente hidrógeno N–H mientras que la amida B resulta de la resonancia de FERMI de la vibración del estiramiento N-H con el sobretono de la vibración de la amida II [11]. Según Burgardt et al. [10] estas bandas también están relacionadas con el aminoácido prolina, que es abundante en el CMP. Las bandas observadas en 2970 y 2940 cm^{-1} refieren a vibraciones simétricas y asimétricas del grupo metilo ($-CH_3$) [12]. La vibración de la amida I, que es causada principalmente por los estiramientos del enlace C=O, se mide en el rango de 1700 a 1600 cm^{-1}, mientras que, la vibración de la amida II, que se produce por la deformación de los enlaces N-H y por los estiramientos de los enlaces C-N, se mide en el rango de 1600 a 1500 cm^{-1} [13]. Estos son los modos vibracionales más importantes de las amidas. Las frecuencias exactas a las que estos enlaces absorben dependen de la estructura secundaria de las proteínas o péptidos. En el espectro del CMP estas bandas se observan en 1649 cm^{-1} y 1549 cm^{-1}, y se atribuyen a las vibraciones de amida I y II respectivamente. La banda de amida III a 1240 cm^{-1} representa la combinación entre la vibración del estiramiento C-N, la flexión del enlace N-H de la amida y las vibraciones de los grupos CH_2 del esqueleto de la glicina y de las cadenas laterales de la prolina [14].

Una de las bandas especialmente significativas en el CMP es la correspondiente al grupo funcional carboxilato (COO^-). Los carboxilatos producen una vibración a los 1400 cm^{-1} que caracteriza la coordinación de los iones metálicos divalentes [15]. La banda a 1320 cm^{-1} es atribuida al grupo CO-N (amina) [10]. El CMP está glicosilado, y la señal de absorción en la región de la huella digital se encuentra entre 1200 y 1000 cm^{-1} [16]. Según Lewis et al. [17] el ácido siálico tiene una señal característica a 1024 cm^{-1}, la N-Acetilglucosamina (GlcNAc) a 1025 cm^{-1} y la N-Acetilgalactosamina (GalNAc) a 1038 cm^{-1}. Los sitios fosforilados del CMP (Ser 149 y 127) dan una escasa señal a 990 cm^{-1} [18]. Las bandas presentes a 935 y 900 cm^{-1} estarían relacionadas con la galactosa (Burgardt y col., 2014).

3.2 Efecto de la adición de $CaCl_2$ sobre el estado de asociación del CMP por DLS

Con el propósito de analizar el efecto de la concentración de CMP con el tamaño molecular en presencia de $CaCl_2$ se realizaron las mediciones de tamaños de partícula por DLS para dos soluciones de CMP de diferente concentración (10 g/L y 50 g/L) y concentraciones variables de $CaCl_2$ a pH 7,0 y 25 ºC. En ausencia de $CaCl_2$, las distribuciones fueron bimodales para 10 g/L y trimodales para 50 g/L. Sin embargo, la concentración de CMP no influyó en la posición del primer pico, 2,3-2,5 nm. El software del equipo Zetasizer Nano-Zs permitió estimar el grado de asociación molecular en cada caso considerando a la forma monomérica del CMP (aproximadamente 7,5 kDa) de un valor de *d(H)* de 2,6 nm [8]. La Fig. 2 muestra el valor máximo del *d(H)* del pico predominante y los correspondientes estados de asociación obtenidos en presencia de distintas cantidades de $CaCl_2$ para soluciones de CMP con diferente concentración: 10 y 50 g/L. Se observó para las dos concentraciones que el *d(H)* se desplazó hacia tamaños mayores hasta alcanzar un valor máximo (5,6 nm). Es decir, el péptido en presencia de $CaCl_2$ se autoensambló desde monómeros a dímeros, tetrámeros y finalmente hexámeros dependiendo de la concentración de $CaCl_2$ presente en el medio.

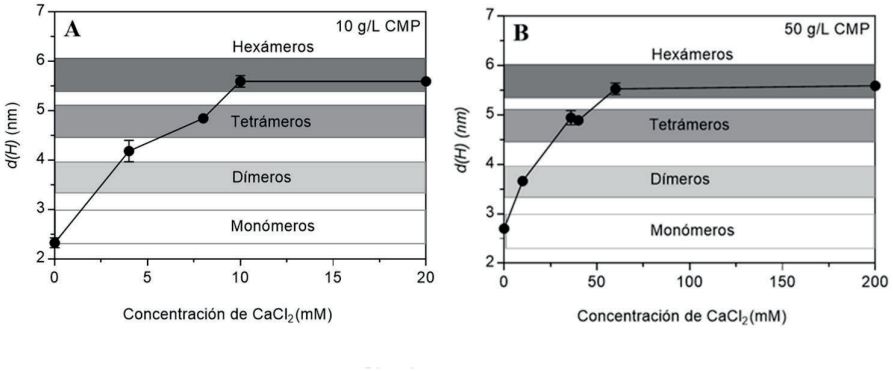

Fig. 2 Valor máximo del *d(H)* del primer pico de la distribución (intensidades) de soluciones de CMP en función de concentraciones crecientes de $CaCl_2$ a pH 7 y 25 ºC. Concentración de CMP: A) 10 g/L y B) 50 g/L. Se indica el estado de asociación predominante estimado mediante el software del equipo Zetasizer Nano-Zs. Las barras representan el desvío estándar.

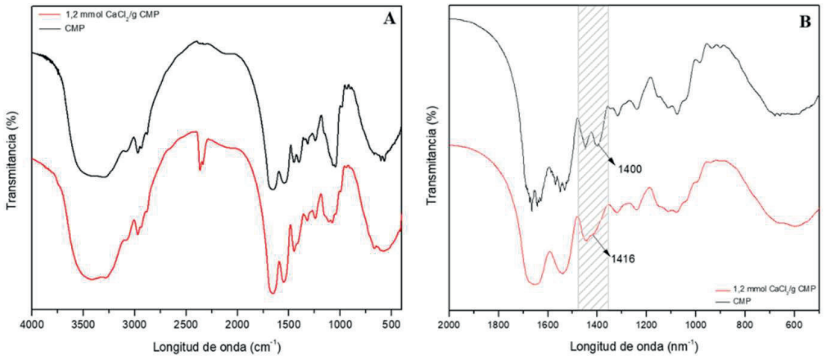

Fig. 3 Espectro FTIR del CMP en ausencia de sales (–) y en presencia de 180 mM de $CaCl_2$ (–). Relación 1,2 mmol $CaCal_2$/ g CMP (A). Vista ampliada entre 500 y 2000 cm^{-1} (B).

Basados en nuestros hallazgos, se puede afirmar que la forma de asociación del CMP en presencia de $CaCl_2$ sigue un mecanismo desde los monómeros hasta los dímeros (0,3 - 0,4 mmoles $CaCl_2$/g de CMP), luego tetrámeros (0,7 - 0,8 mmoles $CaCl_2$/g de CMP), y finalmente hexámeros (1 - 1,2 mmoles $CaCl_2$/g de CMP que equivale a 7,5 -9 mol/mol CMP), donde alcanzó su estado de asociación máximo indicando que esta relación es su máxima capacidad ligante.

3.3 Espectro FTIR del CMP a pH neutro en presencia de $CaCl_2$

Los espectros del CMP en ausencia y presencia de cloruro de calcio se muestran en la Fig. 3 y las asignaciones en la Tabla 1. Se eligió la concentración óptima que se observó previamente en los estudios previos de DLS de 1,2 mmoles de $CaCl_2$/g CMP. Al comparar los dos espectros (con y sin $CaCl_2$) de la Fig 3A, se distinguen diferencias que brindan información en la estructura molecular, por ejemplo, desplazamientos hacia el rojo o hacia el azul, incremento o reducción de picos. La absorción a alta frecuencia de 3301 cm^{-1} (Amida 2º A) que se atribuye a la vibración de estiramientos N-H cambió a 3283 cm^{-1} y el de la Amida 2º B de 3080 a 3088 cm^{-1}. Este cambio podría deberse a que los grupos N-H se reemplazarían por uniones N-Ca como describieron Peng et al. [19] y Wang et al. [9] para otros péptidos. La banda de Amida I a 1649 cm^{-1} para el CMP/$CaCl_2$, se debería a que los grupos C-O participarían en la interacción del péptido con el Ca^{2+} [20]. En la región de la Amida II han desaparecido los picos correspondientes al número de onda 1535 y 1545 cm^{-1}, encontrándose un valle en el espectro del CMP/$CaCl_2$. Fundamentalmente, la banda de 1400 cm^{-1} correspondiente a los grupos carboxílicos (COO^-) se desplazó hacia frecuencias mayores (1416 cm^{-1}) en el espectro del CMP/$CaCl_2$ (Fig. 3B).

Wang et al. [9] estudiaron a través de espectroscopía FTIR el efecto de la interacción del $CaCl_2$ y un péptido proveniente de la fermentación con *B. subtilis* de semillas de pepino. Los autores hallaron, al comparar el espectro en ausencia y presencia de calcio, cambios similares a los de esta tesis. Encontraron un pico a 3416 cm^{-1} que se desplazó a 3424 cm^{-1} que atribuyeron a la participación de los grupos -NH en la coordinación con el Ca^{2+}. Los autores observaron un desplazamiento desde 1402 cm^{-1} en el espectro del péptido libre hacia frecuencias mayores (1420 cm^{-1}) en presencia de calcio y lo atribuyeron al estiramiento del grupo carboxilato $–COO^-$ por la combinación con Ca^{2+} para formar –COO-Ca. Finalmente, concluyeron que los principales sitios de coordinación entre el calcio y el péptido estudiado fueron los grupos –COOH, -OH, $-NH_2$ y –CO-NH.

Por otro lado, Peng et al. [19] estudiaron la afinidad por el $CaCl_2$ de un péptido proveniente del colágeno de hueso de pescado (*Gadus macrocephalus*). El espectro FTIR del péptido con calcio mostró que la banda de 3381 cm^{-1} se desplazó a 3361 cm^{-1}, la banda correspondiente a la vibración de amida I (1646 cm^{-1}) se desplazó a 1658 cm^{-1} y la de amida II (1558 cm^{-1}) a 1549 cm^{-1}. Además, la banda de 1455 cm^{-1} se desplazó a 1411 cm^{-1}. Los autores concluyeron, a partir de los cambios observados por esta técnica, que ese péptido quela iones calcio principalmente a través de interacciones con los átomos del nitrógeno del grupo amino y los átomos de oxígeno del grupo carboxílico. Los péptidos con gran afinidad por el calcio típicamente contienen una gran cantidad de Glu y Asp, ya que contribuyen a la unión del calcio posiblemente al generar un ambiente ácido para que los cationes se coordinen [19]. Las proteínas del hueso de pescado contienen altas proporciones de Gly, Glu y Arg, que tienen una alta afinidad por el calcio. En la secuencia aminoacídica de la variante A del CMP se encuentran 10 de estos aminoácidos ácidos: 8 residuos de Glu y 2 de Asp. Otras investigaciones [21, 22] muestran que los aminoácidos básicos también tienen afinidad con el calcio principalmente causada por los grupos $–NH_2$ o –NH que pueden participar en la coordinación con el calcio. Los aminoácidos básicos son: Lys, Arg y His, de los cuales el CMP contiene 3 residuos de Lys.

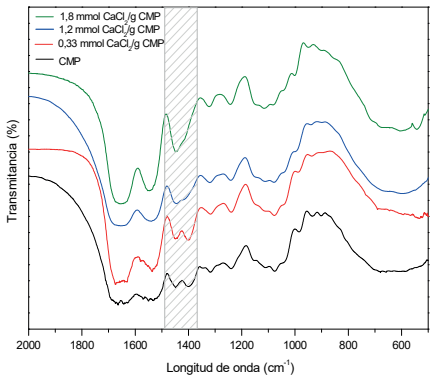

Figura 4. Espectro FTIR del CMP con diferentes relaciones $CaCl_2$/CMP, desde 2000 a 500 cm^{-1}.

En la Fig. 4 se muestran los espectros FTIR del CMP con diferentes concentraciones de $CaCl_2$. Las relaciones entre el $CaCl_2$ y el CMP están informadas en cada uno de los espectros y son: 0,33; 1,2 y 1,8 mmol de $CaCl_2$/g de CMP. Se eligieron estas relaciones a partir de los resultados hallados en DLS, buscando analizar la interacción molecular del CMP y el calcio en una relación por encima y por debajo de la hallada como óptima (1,2 mmol de $CaCl_2$/g CMP). En los espectros superpuestos de la Fig. 4 puede apreciarse que el corrimiento del pico de 1400 cm^{-1} a 1416 cm^{-1} sólo se observa para una relación $CaCl_2$/CMP igual o superior a 1,2 mmoles de Ca^{2+}/g. Esto indica que debe existir una cierta cantidad de iones Ca^{2+} en el medio para propiciar la unión con el CMP.

4. Conclusiones

A pH 7,0, el CMP se encuentra formando moléculas individuales (monómeros), pero si se adiciona $CaCl_2$, las cargas electroestáticas se apantallan y los residuos hidrofóbicos de la molécula de CMP pueden interaccionar. Los resultados de DLS indicaron que cuando la concentración de cloruro de calcio es superior a una relación 1,2 mmol $CaCl_2$/g de CMP, se alcanza el máximo estado de asociación, un hexámero. Este cambio en el tamaño es indicativo de una interacción molecular con el $CaCl_2$. Los espectros FTIR de CMP/$CaCl_2$ confirmaron que en presencia de calcio iónico se evidencia principalmente un corrimiento en la posición de los grupos carboxilatos (COO-) desde 1400 cm^{-1} a 1416 cm^{-1} que indicarían interacción para la misma relación de 1,2 mmoles de $Ca^{2+/}$g CMP o superior. Dada la potencialidad del CMP como péptido ligante, este trabajo plantea un nuevo ingrediente funcional con alto valor agregado.

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Project Management Process Resilience: Assessing and Improving the Project Review Process Using FRAM

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Abstract. Technology development projects are constantly subject to risks and uncertainties and their performance are key to deliver the organizational value. Failing to meet project goals and objectives is critical, therefore, projects must be able to cope with an environment of complexity and pressure. This paper aims to assess and improve project resilience by using the Functional Resonance Analysis Model (FRAM) to look at project review process, a stage-gate milestone typical to Systems Engineering process. FRAM is supported by the Resilience Engineering perspective that things go wrong by the same reasons they go right, and everyday work is subject to variability and small adjustments, which is key to address such project environments. After assessing sources of variability and aggregating them, means to manage variability are proposed order to increase process resilience.

Keywords: Project Management, Resilience Engineering, FRAM.

1 Introduction

Technology-intensive projects are subject to complex environments and high levels of risk and uncertainty and require multidisciplinary approaches to meet their strategic objectives [1]. Resilience engineering focuses on helping people to achieve success while coping with complexity under pressure [2]. If risk management is entirely associated with Project Management and Systems Engineering [3], project resilience is one of the emerging topics in the area [4] and, along with Resilience, Resilience Engineering is described by Aven [5] as recent advances in the foundations of risk assessment and management.

This work aims to assess and improve project resilience in the context of the Institute of Aeronautics and Space (Instituto de Aeronáutica e Espaço, IAE), an organization from the Brazilian Air Force that defines its mission as "to develop technological and scientific solutions to strengthen Brazilian Aerospace power through research, development, innovation […] in aeronautical, space and defense systems" [6]. IAE, as a project-oriented organization, uses Systems Engineering, a process-oriented product life cycle management approach that enable developers to evolve from customers' needs to product delivery [7]. Systems Engineering may be seen either as a function within the

Project Management process [8], or a whole process that intersect with Project Management functions [9]. Project reviews, or design reviews, are gates that set decision-making milestones and determine whether the project is heading towards its original goals and the design has met criteria for the corresponding Systems Engineering process phase, aiding project control process and reducing risks and uncertainties during the development [10]. This work aims exclusively on project reviews.

All these processes are subject to variability and small adjustments, given that every project is unique. Functional Resonance Analysis Method (FRAM) aims to describe everyday performance model performance variability in complex dynamic socio-technical systems [11] and may be used in order to assess and find ways to manage variability and improve resilience within an interest system. Although originally imagined by Eric Hollnagel for modelling socio-technical systems [12], in this work FRAM will be applied in an essentially organizational process: the project review process.

This paper is divided into 6 sections. In section 2, a brief introduction to Resilience, Variability and FRAM will set the scene for the case study, the project review process in IAE, which will be discussed in section 3. Initial steps of FRAM will be applied for modelling work-as-done and assessing variability in section 4, then different scenarios for instantiations will be considered for later steps to establish ways to manage and improve resilience management of the process in section 5. Finally, an overview of the work as done in the conclusion and some insights for future works are provided.

2 Resilience, Variability and FRAM

2.1 Resilience and Resilience Engineering

Resilience and Resilience Engineering address issues with respect to the safety of systems, not by looking to things that go wrong, as usually do traditional approaches to safety, but by also looking to things that go right. It emerges as a consequence of understanding that both situations derive from the same circumstances: performance in sociotechnical contexts vary with time [13] and, as a conclusion, Resilience Engineering defines safety as “the ability to succeed under varying conditions” [14]. The perspective given by resilience is key to address modern context, in which traditional risk frames alone may not be enough and, therefore, both approaches should be considered together [15].

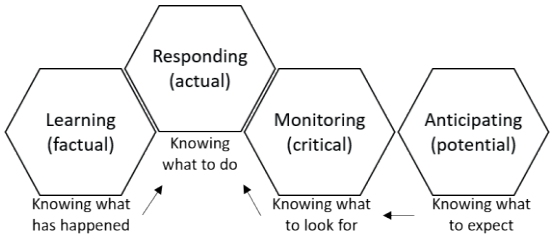

Fig. 1. The four cornerstones of resilience engineering [14, p. xxxvii]

Resilience is supported upon four cornerstones, as seen on Fig. 1, that can be improved within the context of a system [14]: responding (actual), which is dealing with what is already expected or considered normal behavior within minimal adjustments; monitoring (critical), that is observing the environment and the system in order to find threats; anticipating (potential): expecting potential developments, opportunities, and threats; and learning (factual): acquiring the right experience from both successes and failures.

2.2 Functional Resonance Analysis Method – FRAM

Functional Resonance Analysis Method (FRAM) was proposed by Erik Hollnagel in 2004 and developed in congruence with the principles of Resilience Engineering [11]. It introduces two key concepts: work-as-imagined (WAI) and work-as-done (WAD). Work-as-imagined can be understood as the task list or the process flowchart, in which things must be done the way it was meant to, in a linear thinking. Work-as-done perspective, on the other hand, provides the understanding that operators adjust their everyday operation with variations and small adjustments conditioned to the environment and other circumstances and, therefore, perform their work not necessarily according to the WAI, yet do not incur in a failure, from a traditional safety perspective [12].

FRAM defines system as "a set of coupled or mutually dependent functions" [12, p. 17] and model the relationship between these functions from a systemic perspective, which means properties may emerge from variability and resonate within the system. Functions in FRAM are coupled to each other through six aspects: input (the which is processed through the function), time (which determines a temporal constraint), preconditions (which must be met for the function to be performed), resources (which are consumed during the performance), control (which determines control or monitoring conditions during the performance), and the output (which may be an entity or a state change). Fig. 2 shows how a function is represented when modelled with FRAM.

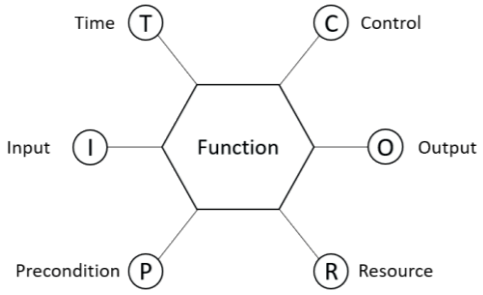

Fig. 2. A hexagon representing a function [12, p. 48]

FRAM is built upon four principles [12]: "equivalence of failures and successes": things go wrong by the same reason they go right; "approximate adjustments": everyday performance adjusted to match its conditions; "emergence": in the systemic sense, that the outcomes, predicted or not, must be described as emergent rather than resulted; and "resonance": relations and dependencies among functions are not cause-effect links, but they develop from a specific situation and context.

Hollnagel proposes four steps for using FRAM and one, which is necessary prior to the analysis, called "Step 0", in which the purpose of the analysis is determined. FRAM may be used either for event investigation (to look at what have happened) or for risk assessment (to predict what may happen in the future). Step 1 identifies the functions and describes how something is done through connecting the functions' aspects, then Step 2 will characterize potential and actual variability in FRAM. Then, Step 3 will aggregate variability by looking at specific instantiations of the model and, finally, Step 4 allows the user to propose ways to manage performance variability.

2.3 Evaluating the Process Performance Variability

Hollnagel proposes in step 3 a method for the aggregation of variability as a result of the upstream-downstream couplings for the aspects of every function [12]. His method, however, was essentially qualitative. In 2010, Luigi Macchi [16] proposed an increment for Hollnagel's approach for agregating variability through an application of the FRAM giving integer scores for aspect's qualities. For every function, its upstream aspects are assessed with respect to its quality, then this is related to how performance variability may be dumped or amplified. Table 1 links temporal and precision to quality of aspects, and Fig. 3 relates quality of aspect to potential for increasing or decreasing variability.

Table 1. Characterization of functions' output [16, p. 73]

		Temporal characteristics		
		Too early	On time	Too late
Precision	Precise	**A:** output to downstream functions is precise but too early	**B:** output to downstream functions is precise with the right timing	**C:** output to downstream functions is precise but delayed, reducing available time
	Appropriate	**D:** output to downstream functions is appropriate but too early	**E:** output to downstream functions is appropriate with the right timing	**F:** output to downstream functions is appropriate but delayed, reducing available time
	Imprecise	**G:** output to downstream functions is imprecise and too late	**H:** output to downstream functions is imprecise but correctly timed	**I:** output to downstream functions is imprecise as well as delayed, reducing available time

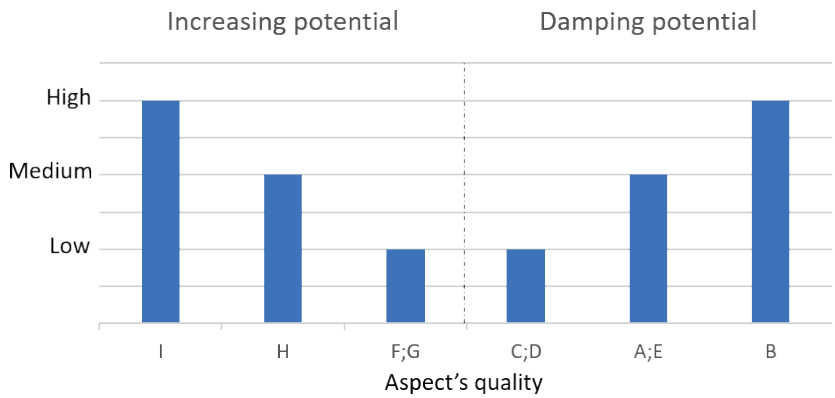

Fig. 3. Increasing and damping potential as a function of the aspect's quality [16]

Scores corresponding to the potential for increasing are positive (+) and, for damping, are negative (-), and the values for high, medium, and low are respectively +/- 3, +/- 2 and +/- 1. The quality of the output of a function would, then, be determined by the median of the quality of the *n* aspects provided by functions upstream as in (1).

$$q_o = \text{median}\left(q_{a_1}, q_{a_2}, \ldots, q_{a_n}\right) \quad (1)$$

For this work, another factor considered was complexity of a function, rather than precision and timely aspects. Complexity will be a source of variability if operator is not well trained or used to the function they are supposed to perform. Scores are also given considering low, medium, or high potential for damping or increasing variability.

3 Case Study: Systems Engineering Project Reviews in IAE

3.1 Systems Engineering Process in IAE

The Instituto de Aeronáutica e Espaço, as a project-oriented organization, has developed its own processes for Project Management and Systems Engineering, aligned with standards and good practices and the procedures for product lifecycle [17] and project lifecycle [18] at the Brazilian Air Force. The results are two internal standards for project and product lifecycle phases, and one for project review procedures. For aeronautical and defense systems, the phases of product development and their main project reviews are described in Fig. 4.

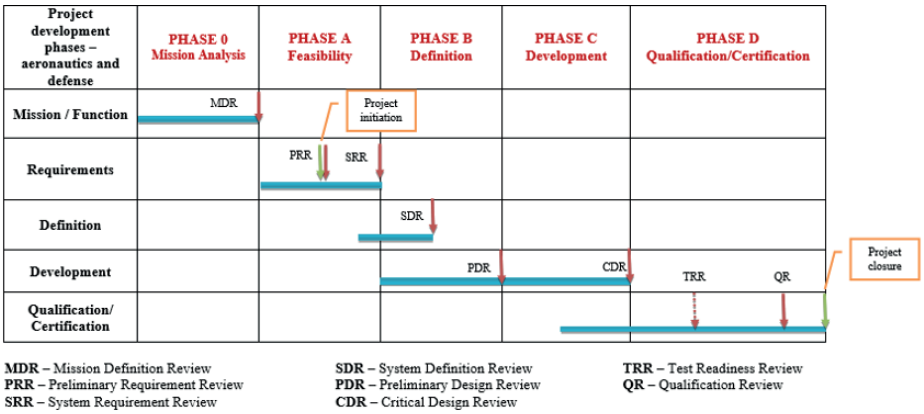

Fig. 4. Phases of product development and typical project reviews in IAE [19].

3.2 Project Review Process

Project reviews are milestones in which an independent group of experts evaluate whether the project is heading towards its original goals and meeting the phase criteria or not [20-21]. If the project meets the requirements as stated in the standards, or a subset of requirements, justified by a tailoring process, the project is considered approved to proceed to the next phase. If the project fails to meet all the requirements, it may either be approved, conditioned to meeting the requirements in time for the next milestone, or it is considered reproved and review must be retaken.

The "Project Review Procedures" internal standard [22] was developed by the Systems Engineering Office (SEO), derived from some international standards and procedures [23-25], and it represents a description for the work-as-imagined (WAI). Its last appendix shows a process flow using Business Process Model Notation. As already discussed in section 2.2, this is a result of a straight linear thinking and likely not to describe the real work-as-done (WAD), but it is helpful when modelling the WAD.

There are 3 main groups or actors involved with the process: the Project Review Team (PRT), who will be responsible for representing the whole project team and giving all the information necessary; the Review Committee (RC), which consists of invited and independent experts, who will be responsible for assessing the project and the evidence provided by the PRT; and the Review Authority, who acts as a moderator and is responsible for process quality assurance and ensuring that Review Committee (RC) works independently and free of political pressure.

The Project Review Process consists of 4 subprocesses:

1. *Prepare project review*: consists of assigning the Project Review Team (PRT), gathering the evidence that the criteria for the selected milestone were met, inviting experts for the Review Committee (RC), communicating to the SEO the intention of conducting a review and planning the next steps (communications, meetings, etc.)
2. *Assess evidence*: PRT discloses the initial data pack with documents and evidence, which shall be assessed by the RC. Comments and questions are issued in

"Comments and Questions Register" (CQR), which will be relied by an appointed PRT member. This goes on until register is scheduled to be consolidated by the PRT.
3. *Assess project*: RC presents its initial conclusions at a Coordination Meeting. From RC's considerations, they issue Review Item Discrepancies (RIDs), to be addressed by the PRT. Answers to the RIDs are assessed by the RC, who will consider whether answers are adequate or not to fix the discrepancies.
4. *Close review process*: RC shall present its final conclusions after evaluating RID's answers and approve if all milestone criteria were met, recommend conditional approval, or deny approval. Conditional approval needs Portfolio manager's approval. After Review Authority consent, review process shall be evaluated by its participants and a final report is issued.

4 Modelling the Work-as-Done

Before initiating Step 1, it is necessary to determine the purpose of the analysis. As stated in the introduction, this work aims to assess and find ways to improve the resilience by looking at the project review process. Therefore, the purpose is to predict what may happen in the future, but with a particularity: project reviews process are supposed to happen several times during a project life cycle, so monitoring work actually "as-done" will give further information and provide feedback to validate the model.

4.1 Step 1: Identifying and Describing Functions

FRAM modelling of the process was aided by the process flow given by the project review standard [22] and by monitoring the Mission Definition Review (MDR) for the Project IFF Mode 4 NSM, which is currently under development by IAE [26]. The model was done using the FRAM Model Visualizer (FMV) [27].

All four subprocesses described in section 3.2 were modelled from work-as-imagined (WAI) into work-as-done (WAD) and their functions were collapsed into a high-level perspective, as seen in Fig. 5. Functions in green are the 4 subprocesses, and functions in purple and red are background functions, which are not a direct part of the main process, yet they are sources of variability and must be considered for the next steps.

4.2 Step 2: Characterizing potential and actual variability

From the observed MDR process, subprocess 2, "Assess evidence" raised a flag and, therefore, was taken into consideration for further analysis. The interaction between PRT and RC did not work as imagined, which considered a loop of comments and questions continuously being replied. Although the interaction happened, there was little feedback to the process, and few comments and questions were reassessed by RC. Fig. 6 shows WAI for subprocess 2, and Fig. 7 show its WAD, modelled with FRAM, in which green functions are organizational considered in WAI model, yellow functions are human functions considered in WAI, red functions are human functions not considered in WAI and grey functions are background functions.



Fig. 5. FRAM model of the high-level project review process.

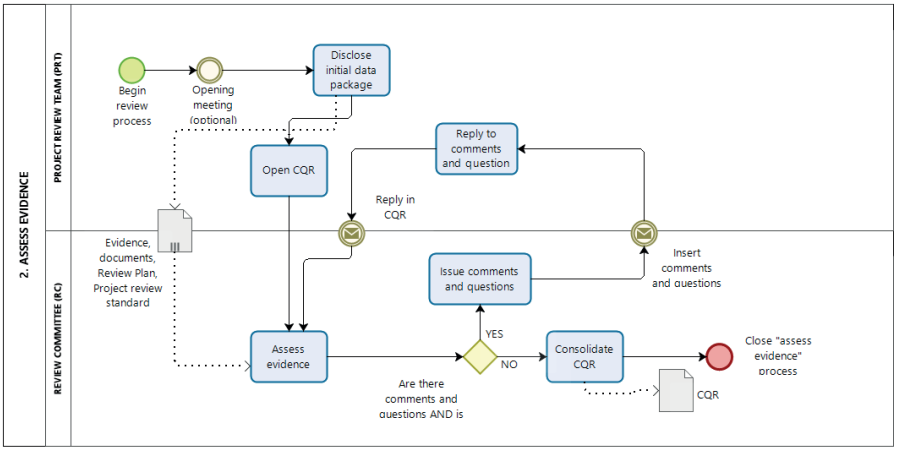

Fig. 6. Work-as-imagined (WAI) for subprocess "2. Assess evidence".

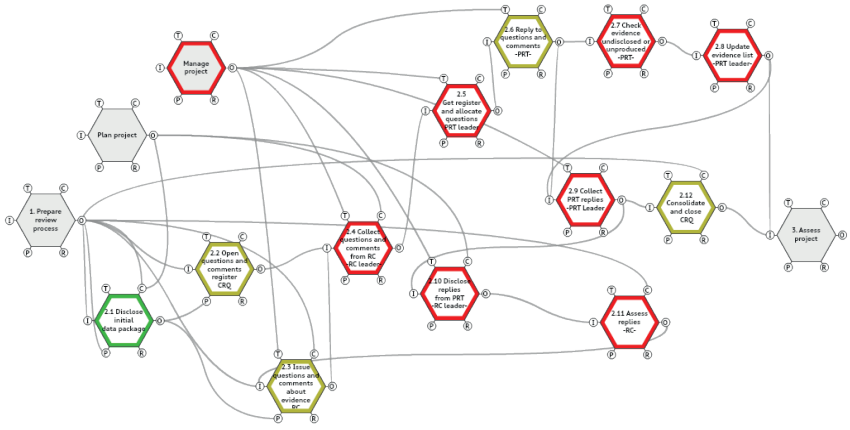

Fig. 7. FRAM model for subprocess "2. Assess evidence" work-as-done (WAD).

Functions, with their respective outputs, are described in Table 2. The output flow goes downstream up to a feedback, as seen in the WAI, in which replies are assessed by the RC and give them more information to interactively assess the evidence.

Table 2. Functions in subprocess 2 and their outputs

Nº	Function	Output	
2.1	Disclose initial data package	Data package disclosed	
2.3	Issue questions and comments about evidence	Comments and questions	
2.4	Collect questions and comments from RC	CQR with questions and comments	
2.5	Get CQR and assign questions to PRT	Questions and comments allocated	
2.6	Reply questions and comments	Questions and comments replied	
2.9	Collect PRT replies	CQR with replies	
2.10	Disclose replies to RC	CQR with replies disclosed	
2.11	Assess replies	Replies assessed	
2.12	Consolidate and close CQR	CQR consolidated	

FEEDBACK

Here is a brief description of each function:

- 2.1 – Disclose initial data package: as the review process begin, the RC shall receive the data package to assess the evidence. Review plan helps to set a deadline for disclosing, but this may vary. RC members should also sign a confidentiality agreement if the project data access is restricted, which is the case for most projects in IAE.
- 2.3 – Issue comments and questions about evidence: RC members, experts invited due to their experience with other development projects, shall assess the evidence. Usually, there is a need for clarification, therefore comments and questions are issued. The quality of this process depends on the RC members expertise, which is defined in subprocess 1. Prepare Review.
- 2.4 – Collect questions and comments from RC – Review Committee leader shall gather every RC members' comments and questions and send them to the Project Review Team leader.
- 2.5 – Get CQR and assign questions to PRT: PRT leader shall assign questions and comments to be replied by the project team member that deals with the matter.
- 2.6 – Reply questions and comments: PRT member assigned by the PRT leader shall reply to their comments and questions and send them back to the PRT leader.
- 2.9 – Collect PRT replies: as PRT members reply to their assigned questions and comments, PRT leader shall collect them to send a new version of the CQR to RC leader.
- 2.10 – Disclose replies to RC: RC leader discloses the latest CQR version to the other RC members.

- 2.11 – Assess replies: RC members assess replies given by PRT members, considering if further information is required and, so, issuing new comments or questions.
- 2.12 – Consolidate and close CQR: Review Plan defines, in its schedule, a deadline for the subprocess 2, whether assessment had been successfully done or not. After the deadline, review process proceeds to the next step, at the Coordination Meeting.

Background functions must also be considered for the resilience assessment. In this organizational process, they play a major role as a source of variability with respect to the quality of their outputs, either from a precision/timely (P/T) perspective or from a complexity (C) perspective. Table 3 gives further detail on background functions and quality of their outputs and Table 4 relates background functions and functions of subprocess 2 with respect to their aspects (I – input, P – precondition, R – resource, T – time, and C – control).

Table 3. Background functions and their outputs

Function	Output	Description
0.1 Manage project	Pressure upon review schedule (C)	Determined by Project Manager's expertise and approach to the team. A healthy pressure may lightly damp variability (-1), whereas lack of expertise or excessive pressure may amplify variability (+2 or +3).
	A. Project Review Plan (C)	Project Review Plan has little effect over the process, although it establishes a schedule and enlightens stakeholders with respect to their roles and responsibilities, which may be regarded as a low damp factor (-1).
	B. RC members expertise (C)	Depending on the expertise of the invited members of RC, good knowledge of the industry or with past similar projects damp variability (-1 or -2), whereas lack of expertise or knowledge of the subject of the review, or even the review process itself, may be a factor that amplifies variability (+1 or +2).
1. Prepare review	C. Initial list of evidence (P/T)	Usually delivered on time (D, -1). If project manager is unexperienced or do not pay attention to producing the evidence prior to the milestone, then output quality may be imprecise (H, +2).
	D. Signed confidentiality agreements (P/T)	Usually, delivered too late. There is no record of inappropriate output, which would mean RC member would not take part in the process. (F, +1).
	E. Data package ready for distribution (P/T)	Usually, delivered on time, but not usually precise, because typically there is a need to add new information to the initial data package (E, -1). Level of access may couple and delay the distribution (F, +1).
0.2 Plan project	Documentation level of access (C)	R&D projects at IAE usually are classified and this adds complexity to the process, especially regarding data transmission. Medium or high potential to amplify variability (+2 or +3).

Table 4. Relationship between background functions outputs and functions' aspects at subprocess "2. Assess evidence"

	2.1	2.3	2.4	2.5	2.6	2.9	2.10	2.11	2.12
0.1		T	T	T	T	T	T		
0.2	C	C	C				C		
1.A	C	C							T
1.B		C						C	
1.C		I							
1.D	P								
1.E	I								

5 Improving the Process Resilience

5.1 Step 3: Aggregating variability

After steps 1 and 2, step 3 will aggregate variability and step 4 will propose ways to manage variability. Once it was possible to monitor one round during the Project IFF Mode 4 NSM Mission Definition Review, one of the scenarios for aggregating variability will be the work-as-done. Other four scenario will be considered, using two variables: Project Manager expertise, which impacts output of background function 0.1, and RC members expertise, which impacts output B for background function 1. "Prepare Review". Both variables will have a "best-case" and a "worst-case" scenario. For instantiation where both are "best-case" scenario, a "worst-case" scenario will be added for level of access, adding more complexity to the process through output of background function 0.2. Table 5 gives all five instantiations scenarios and Table 6 gives relative scores with respect to potential for damping or amplifying variability for each scenario. Using the variability aggregation method as in section 2.3, scores were propagated through the functions and the results can be seen in Fig. 8.

Table 5. Instantiation scenarios

SCENARIOS	PM expertise & attitude		RC expertise		Level of access
	BEST	WORST	BEST	WORST	
WAD	WORK AS DONE				
Scenario 1		X		X	REGULAR
Scenario 2	X		X		HIGH
Scenario 3	X			X	REGULAR
Scenario 4		X	X		REGULAR

Table 6. Scores for the instantiation scenarios

Function / output		Scenario				
		WAD	1	2	3	4
0.1	Schedule pressure	2	3	-1	-1	3
1.A	Review plan	-1	-1	-1	-1	-1
1.B	RC expertise	-1	2	-1	2	-2
1.C	Initial data list of evidence	1	2	-1	-1	2
1.D	Confidentiality agreements	1	1	1	1	1
1.E	Data pack ready	1	1	1	1	1
0.2	Level of access	2	2	3	2	2

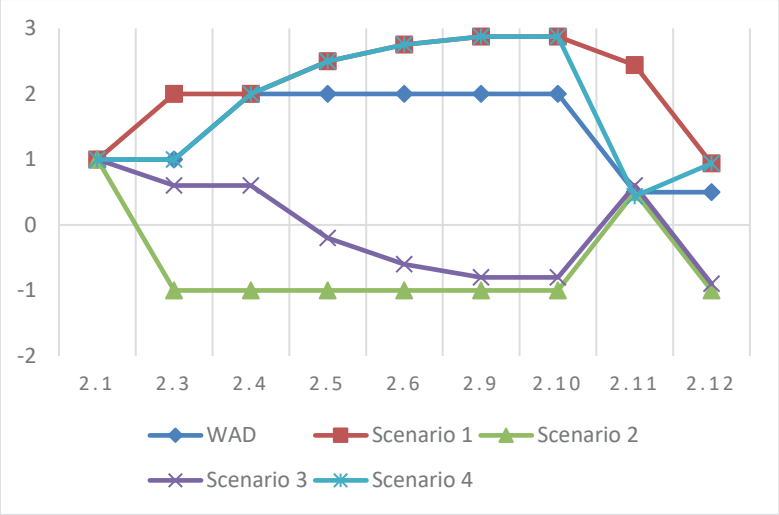

Fig. 8. Aggregation of variability and propagation through the process

5.2 Step 4: Managing variability

From the results in Fig. 8, three main findings may be drawn. Firstly, the results from the WAD scenario reflect how the process was performed. As stated in section 4.2, there was little interaction after comments and questions were replied by the PRT. This was partially due to the comments being issued with precision, but too late (F, +1), which is exactly the model quality output for function 2.3. Functions downstream were performed out of time or not even performed, which is in accordance with the results given by the model.

Secondly, Comments and Questions Register (CQR) consolidation is an event with a clear deadline, given by the Review plan, and is a pre-requisite to execute the Coordination Meeting, a mandatory event within the process. Output quality score of function 2.12 drops in almost every scenario (except in scenario 4), which was expected.

Output quality +1 may indicate issues with precision, which can be translated into information quality. This is the case for both scenarios in which RC expertise is at worst-case scenario, and, hence, justified.

Finally, the Project Manager attitude and expertise play a major role in the variability aggregation. A skilled, well-trained project manager, with a good attitude, will cope with adjustments necessary after planning is done and help their team towards meeting the process objectives with more ease. This impacts other functions, mostly related to the Project Management processes, such as risk management and leadership, which will keep team motivation and readiness levels high. If, on the other hand, the project manager is unexperienced, lack of attitude or puts too much pressure on their team, variability will be amplified, as seen in scenarios 1 and 4. This last conclusion could have been found in other sources that discuss the role of the project manager and good project management practices [4, 28-29], but it shows that the model gives results that are coherent with the main bodies of knowledge.

In order to close step 4 and the whole FRAM analysis, there are two actions which are suggested to manage variability. Firstly, to provide better training and environment for Project Managers. Well trained PM can manage their own team and to oversee the whole process from both project management and systems engineering, which will help them to increase the whole Systems Engineering process resilience. Also, good PMs will allow room for small adjustments to the original plans, should things work differently than expected (which they do). The second action, which is coupled to the first, is to give clearer instructions to participants within the project review process. This will help participants to clearly understand their roles and responsibilities, especially those external experts invited to the Review Committee, who may not be familiar with the whole review process. Resilience principles, however, must be considered: there must be room for small adjustments whenever they arise.

6 Conclusion

After going through the four steps of FRAM, plus its step 0, the project review process may now have its resilience improved by the findings of the last step, such as investing in Project Management qualification and providing an environment where project may adapt within the circumstances of their execution, therefore reaching the work's objective as stated in the Introduction. The Functional Resonance Analysis Method, although imagined to modelling social-technical problems, proved to be fit to model an organizational problem and provided interesting insights that are coherent with good practices, such as investing in Project Managers' training and career, in order to improve their capability to cope with variability, and establishing clearly to participants their roles and responsibilities. Everyday work is subject to variability and minimal adjustments, so it is important to determine ways to manage this variability and avoid resonances that would crush system stability.

For future works, it would be interesting to expand the scope of the analysis and assess relationship between Systems Engineering and Project Management processes, respectively product and project life cycle management tools. In an organization such

as IAE, technology development projects are its day-to-day operations, which are subject to variability, and may have its resilience improved with the help of FRAM.

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Medios de pago electrónicos y evasión tributaria: el caso argentino

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Resumen. Este trabajo compara los costos de medios de pago e impositivos asociados a ventas cobradas bajo diferentes modalidades (efectivo, medios bancarios y billeteras virtuales) y sensibiliza estos resultados ante incrementos de actividad o subdeclaración de ingresos. Metodológicamente se efectúa un análisis de caso simulado (microempresa de Bahía Blanca, Argentina) para dos regímenes tributarios: general y simplificado. Para ambos tipos de contribuyentes, el efectivo, el envío de dinero mediante billeteras virtuales y las transferencias son los medios de pago más económicos; mientras que las tarjetas de crédito, el *point* y el *link* de pago resultan los más onerosos. En términos relativos, la empresa adherida al régimen general afronta menores costos por medios de pago y mayores costos tributarios, respecto a la suscrita al régimen simplificado. La subdeclaración del 30 % de los ingresos en efectivo reduce a la mitad los costos impositivos por peso de ventas. El principal limitante a la adopción de medios electrónicos de pago en firmas pequeñas se asocia a la informalidad y no a los costos de transacción.

Palabras claves: informalidad, costos de transacción, regímenes tributarios.

1 Introducción

En la actualidad, a la tradicional opción de cancelación de una transacción en efectivo, se suman diferentes medios electrónicos de pago[1] cuya variedad y nivel de utilización experimentan desde hace tiempo un importante proceso de crecimiento, en algunos casos debido a la obligatoriedad de uso establecida por organismos fiscales. Dichos medios pueden ser bancarios -integrados por las modalidades más clásicas como las transferencias y las tarjetas de débito y crédito- o no bancarios –constituidos por las

[1] Este trabajo analiza diferentes modalidades de cobro. Sin embargo, se emplea el concepto "medios electrónicos de pago" por ser la terminología más difundida y utilizada por el BCRA, entendiéndose como inclusiva de formas electrónicas de pago o cobro. Asimismo, los adjetivos electrónicos, digitales y virtuales se emplean como sinónimos en el presente manuscrito.

alternativas ofrecidas por las billeteras virtuales: *link* de pago, envío de dinero, *point*, código QR (del inglés *Quick Response code*). La multiplicidad de opciones existentes para el pago de las operaciones implica una tarea adicional –tanto por parte de compradores como de vendedores- de evaluación de los costos y las ventajas de cada medio electrónico, y su comparación con el tradicional efectivo, a fin de optar por el más conveniente o acorde a las necesidades.

Si bien la comparación de los medios de pago disponibles puede parecer una tarea sencilla, la complejidad del análisis radica en la cantidad de factores que intervienen y la interacción entre ellos. En primer lugar, cada medio de pago conlleva costos y beneficios asociados. Las ventas en efectivo tienen bajos gastos directos, mientras que las cobradas por modalidades electrónicas implican mayores costos de transacción, pero permiten incrementar los niveles de actividad si se combina con operaciones *online*. En segunda instancia, adquiere importancia el componente impositivo porque, dependiendo de la tipología tributaria del contribuyente, los impuestos se calculan luego de deducir los gastos financieros de la modalidad de pago y, adicionalmente, ciertos medios electrónicos están sujetos a regímenes de retención.

Como tercera cuestión, en un país donde cerca de un tercio del Producto Bruto Interno (PBI) se genera en las sombras [1] y con bajos niveles de educación financiera de la población [2], resulta difícil desalentar el uso del efectivo para la instrumentación de transacciones, por tratarse de un medio de que es fácil de usar y difícil de rastrear [3]. Esta situación agrega al análisis un factor adicional: la flexibilidad que brinda el efectivo a fines de evasión tributaria por subdeclaración de ventas. Incluso, la evaluación se complejiza aún más porque los tres aspectos mencionados (costos de los medios de pago, impositivos[2] y ahorro fiscal por subfacturación) dependen a su vez del régimen tributario al que pertenece el contribuyente.

Además, es necesario destacar que la irrupción de la pandemia causada por el COVID-19 y las medidas de aislamiento social dictadas en consecuencia, han provocado importantes transformaciones en los factores descriptos anteriormente: se produjo un incremento exponencial del comercio electrónico y de los medios de pago digitales; y, al mismo tiempo, se redujo el uso de efectivo tanto por razones vinculadas a la modalidad de venta (plataformas en línea) como por cuestiones de higiene.

Como se describe en los párrafos precedentes, la relación entre medios electrónicos de pago, aspectos impositivos, preferencia por el efectivo, e informalidad empresarial es compleja y la interacción entre sus componentes resulta afectada por la actual pandemia. En este contexto, el presente artículo tiene por objetivo comparar los costos de medios de pago e impositivos asociados a ventas cobradas bajo diferentes modalidades (efectivo, medios bancarios y alternativas ofrecidas por billeteras virtuales) y sensibilizar estos resultados ante incrementos en el nivel de actividad o subdeclaración de parte de los ingresos. En especial, se examinan tales costos para los distintos regímenes tributarios vigentes en la Argentina (general y simplificado). Metodológicamente se trabaja sobre un estudio de caso simulado representado por una microempresa de la industria alimenticia de la ciudad de Bahía Blanca y, a partir de una serie de parámetros

[2] A lo largo del trabajo el adjetivo impositivo se emplea como sinónimo de tributario, siendo inclusivo de los diferentes tipos de tributos: tasas, impuestos y contribuciones.

y supuestos, se estiman los costos y resultados netos de 11 medios de pago diferentes para dos tipologías tributarias: responsable inscripto (RI) y monotributo (MT).

El artículo se considera de relevancia pues representa un análisis microeconómico desde la perspectiva de la oferta de los aspectos vinculados a la implementación de los medios digitales de pago considerando: sus costos -en relación al uso efectivo-, los aspectos impositivos, los beneficios esperados por el incremento de la actividad y los niveles de declaración de ingresos de la compañía. Si bien se reconocen investigaciones sobre el tema, se trata de análisis macroeconómicos realizados en el contexto europeo. Según tales estudios la tasa de penetración de los métodos de pago electrónico se relaciona de negativamente con la economía informal [3] y de forma positiva con el crecimiento económico global [4-5] o la actividad macroeconómica en la región europea [6]. Incluso se verifica que la crisis financiera de 2008 y el nivel de informalidad de un país son factores que potencian el vínculo positivo entre métodos de pago y PBI [6].

Además de este apartado introductorio, el trabajo se estructura como se describe a continuación. En la sección 2 se exponen los conceptos referidos a formas de venta, medios de pago e informalidad empresarial y se analiza la relación entre los mismos. En el punto 3 de metodología se explica el diseño del caso de estudio y se listan los parámetros y supuestos usados para calibrarlo. En la cuarta sección se exhiben los resultados descriptivos para cada sujeto tributario estudiado y los correspondientes análisis de sensibilidad. Finalmente, en las consideraciones finales se sintetiza la evidencia obtenida, se discuten sus implicancias y se plantean futuras líneas de investigación.

2 Marco de antecedentes

2.1 Formas de venta, medios de pago e informalidad empresarial

Existen cuatro modalidades de concretar operaciones de compra venta dependiendo de la combinación del contexto (presencial, *online*) y del medio empleado para cancelar la transacción (efectivo, electrónico). La distinción entre las opciones se origina en dos cuestiones. Por un lado, el uso de un espacio físico o virtual para el encuentro entre vendedores y compradores e implica –bajo la modalidad *online*- la posibilidad de atender un mercado más amplio no limitado al lugar de emplazamiento del negocio, asumiendo costos logísticos. Por otra parte, el segundo factor diferencial corresponde al medio de pago/cobro usado y representa el objeto de interés este estudio: comparar los costos y resultados asociados a distintas modalidades de cobro y sus efectos tributarios.

Todos los instrumentos de pago tienen costos, aunque los vinculados al manejo del efectivo suelen ser subestimados o poco reconocidos porque dependen del volumen de ventas y no son tan visibles como los asociados a medios electrónicos. El empleo de efectivo conlleva costos de gestión originados en la infraestructura necesaria para el conteo de billetes y el registro de transacciones, que se suman a las potenciales pérdidas por robos, hurtos, errores y riesgo de falsificación [3]. Por su parte, en el caso de las modalidades electrónicas, aparecen costos de transacción como comisiones, mantenimiento de cuenta y alquiler de equipos, aunque dependiendo del medio digital utilizado también pueden generarse costos administrativos. Las transferencias bancarias o envíos de dinero mediante billeteras virtuales, por ejemplo, implican una tarea de seguimiento

entre la operación de compraventa y los fondos recibidos; mientras que los cobros con tarjetas, código QR, botón o *link* de pago requieren menores actividades de organización. Las retenciones impositivas -practicadas por las emisoras de tarjetas, administradores de billeteras virtuales o bancos en las liquidaciones efectuadas- también son un factor de peso al optar por una modalidad electrónica porque -si bien son un crédito impositivo- generan un costo financiero por inmovilización de los fondos retenidos.

Uno de los principales beneficios del uso de medios electrónicos de pago proviene del potencial incremento de operaciones, aunque ello depende de su combinación con modalidades de venta en línea y de factores externos como el nivel de penetración de las modalidades digitales en el contexto (país o región). El impacto de la pandemia en las cuestiones mencionadas se describe en la sección 2.2.

Respecto al efectivo, su utilización puede fundamentarse, siguiendo a Keynes [7], en la teoría de preferencia por la liquidez. Según ésta los individuos eligen contar con sus activos de forma accesible y líquida frente a otras posibilidades por tres motivos: transacción (tener el dinero en efectivo -en lugar de depositarlo en una entidad bancaria- facilita las operaciones básicas y cotidianas); precaución (para afrontar gastos imprevistos de diversos tipos) y especulación (mantener dinero en mano posibilita acceder a transacciones u oportunidades de inversión para obtener beneficios). Además de tales razones, su bajo costo y simplicidad, el uso del efectivo también puede vincularse al fenómeno de la informalidad empresarial dada la dificultad de trazabilidad de las operaciones respecto a las efectuadas por medios electrónicos. En este último caso las transacciones son susceptibles de ser verificadas por el cruzamiento de datos que realizan los organismos de recaudación con las entidades del sistema financiero.

La subdeclaración de ingresos en empresas registradas -o "informalidad parcial" [8]- representa una parte del sector informal y es al mismo tiempo una forma de evasión tributaria [9-10]. Para contextualizar el fenómeno, en el caso de la Argentina cerca de un tercio del PBI se genera en la informalidad [1]; mientras que estimaciones recientes indican que las tasas de evasión ascienden al 33,5 % en el Impuesto al Valor Agregado (IVA) y al 49 % en el Impuesto a las Ganancias (IG) [11-12]. Uno de los principales beneficios de la subfacturación radica en el ahorro fiscal obtenido sobre las ventas no declaradas, aunque también pueden mencionarse otras ventajas como la reducción de requerimientos burocráticos o el incremento de ventas por negociación de descuentos con consumidores finales. Asimismo, la informalidad genera ciertos costos: uso limitado de servicios públicos, dificultad de acceso al financiamiento, organización de sistemas de información desdoblados (operaciones registradas y no registradas), posibles sanciones en caso de detección, exposición a coimas de funcionarios, entre otros.

Parte de las exigencias normativas emitidas por los organismos fiscales de control apuntan a desincentivar las prácticas ilícitas de subfacturación e informalidad obligando a los contribuyentes a emitir comprobantes electrónicos y ofrecer medios de pago digitales. Por lo tanto, en algunos casos los medios de pago ofrecidos por las empresas responden al cumplimiento de una obligación formal y no a una estrategia comercial. En ese sentido, con un cronograma de adopción gradual iniciado en el año 2018, en la Argentina, la Administración Federal de Ingresos Públicos (AFIP) [13] ha generalizado la utilización obligatoria de factura electrónica y del controlador fiscal de nueva tecnología. Asimismo, en abril de 2018 finalizó la agenda de implementación que obligó a

todos los contribuyentes a contar con tarjeta de débito o algún medio electrónico de pago para operaciones de importe superior a $ 100 (pesos argentinos cien).

2.2 Impacto de la pandemia en las modalidades de venta y medios de pago

En el marco de la pandemia por COVID-19, la cuarentena y las medidas de aislamiento social, preventivo y obligatorio (ASPO) han acelerado el proceso de digitalización de las pymes, las cuales implementaron la venta en plataformas de comercio electrónico y el cobro *online*. Según el estudio de una consultora privada, el comercio electrónico en la Argentina registró un crecimiento en facturación del 84 % en el mes de abril -en comparación con un mes promedio del primer trimestre de 2020- y pasó de representar el 2 % de los ingresos por ventas de los negocios al actual 12 % [14].

Además del incremento del *e-commerce*, la pandemia motivó la reducción del uso de efectivo: si bien no existe evidencia médica de que el dinero transmita el virus, las percepciones de que los billetes puedan propagar los patógenos afectan el comportamiento de pago de usuarios y empresas [15]. Según una encuesta reciente de RTi Research en América Latina el 72 % de los consumidores prefiere el uso de tarjetas de débito, el 63 % elige tarjetas de crédito, mientras que el 44% opta por el efectivo [16].

De esta forma, la pandemia por coronavirus cambió significativamente el uso del *e-commerce* y fue un catalizador de pagos digitales tanto desde la oferta como de la demanda. De acuerdo a un estudio de Red Link, en abril de 2020 el Uso del Dinero Electrónico (UDE)[3] creció un 8,3 % respecto a marzo y un 19 % interanual [17]. Por su parte, según un relevamiento de la consultora D'Alessio IROL, durante el ASPO el 62% de los argentinos sondeados admitió haber aumentado el uso de pagos digitales. Las modalidades con mayor incremento fueron las tarjetas de débito (35%), las transferencias por *home banking* (31%), las tarjetas de crédito (22%) y Mercado Pago (17%) [16].

Desde el lado de la oferta, entre el inicio de la cuarentena y mediados de junio de 2020, se registraron 34.400 pymes que adoptaron alguna modalidad de cobro digital de Mercado Pago (web, código QR, *link* de pagos, entre otras) [18]. Específicamente, una de las formas de cobro *online* que más creció en dicha plataforma es el *link* de pagos: la cantidad de operaciones se duplicó en los días de ASPO y la cantidad de comercios creció 90 %. Por su parte, los pagos con código QR, que reducen el riesgo de contagio al evitar manipular billetes y tarjetas, también ganaron participación aunque en menor medida porque corren con la desventaja de la modalidad presencial, salvo cuando el código está en una plataforma digital o se envía por correo electrónico [19].

3 Metodología

3.1 Diseño del caso de estudio y métodos de análisis

Para abordar el objetivo propuesto se trabaja sobre un estudio de caso simulado representado por una microempresa de la industria alimenticia -con venta minorista a

[3] Uso del Dinero Electrónico (UDE Link) incluye los movimientos de dinero a través de cajeros automáticos, computadora o celular, y las diversas aplicaciones para operaciones financieras.

consumidores finales- radicada en la ciudad de Bahía Blanca, Buenos Aires, Argentina[4]. A partir de un conjunto de parámetros y supuestos predefinidos (descriptos en la sección 3.2), se efectúan dos análisis. El primero de carácter descriptivo donde se estiman los costos y resultados netos mensuales de 11 medios de pago diferentes para dos categorizaciones tributarias: régimen general (Responsable Inscripto [RI]) y simplificado (monotributo [MT]). Tales estimaciones contemplan: los costos tributarios y de medios electrónicos de pago -incluido el costo financiero por inmovilización de retenciones- y los beneficios impositivos por subdeclaración de ingresos. Sin embargo, no se incluyen los costos de organización administrativa de cada modalidad de pago (se plantea un nivel de operación bajo, donde los costos diferenciales serían escasos o nulos), ni tampoco se cuantifican otros resultados asociados a la informalidad (por ejemplo, multas, coimas, ventajas por menores requerimientos burocráticos).

En segundo lugar, se realiza un análisis de sensibilidad de los resultados estimados ante dos escenarios: (i) un incremento en el nivel de actividad por la implementación de medios electrónicos de pago; y (ii) la subdeclaración del 30 % de las ventas en efectivo. El porcentaje de subfacturación se define considerando las estimaciones más recientes del fenómeno para la Argentina: en 2016 la economía no oficial representó el 28,65% del PBI [1]. No se contempla otra forma de evasión (como la sobredeclaración de costos). Las sensibilidades calculadas permiten conocer para cada medio electrónico de pago analizado cuál es el incremento de ventas mensual necesario -respecto al nivel inicial- para cubrir: los costos de la modalidad digital (S1); los costos del medio de pago y el ahorro fiscal por subdeclaración del 30 % de las ventas originales en efectivo (S2); y el ahorro fiscal por subdeclaración del 30 % de las ventas de base en efectivo (S3).

3.2 Parámetros y supuestos del modelo

Los medios de pago analizados son los vigentes a mayo de 2020 en la Argentina [20]: efectivo y modalidades electrónicas (Tabla 1). Para las alternativas bancarias[5] se consideran dos opciones: que estén asociadas a una caja de ahorro (CA) –sin costos financieros ni aplicación de tributos por débitos y créditos- o a una cuenta corriente (CC), sujeta a un costo de mantenimiento mensual de $ 559,04 neto de IVA (promedio 10 primeras entidades bancarias según BCRA [20]). En el caso de tarjetas, se estima un importe mensual neto de $ 880 por alquiler de la terminal POS (*Point of Sale*).

Para los medios no bancarios, se seleccionan las opciones y los costos de Mercado Pago por ser la billetera virtual con mayor penetración en la Argentina. El único cargo de la plataforma es una comisión variable que depende del momento de acreditación de las ventas y del medio de pago seleccionado dentro de la billetera electrónica. El *point* se adquiere por única vez y no tiene gasto de mantenimiento mensual. Los porcentajes de comisiones de medios no bancarios de la Tabla 1 se corresponden con la alternativa

[4] Encuadra como microempresa según los límites de ventas anuales por sector de la Secretaría de Emprendedores y de la Pequeña y Mediana Empresa. Se identifica a la firma con ubicación y sector porque los tributos provinciales y municipales varían entre regiones y por actividad.

[5] No se incluye el cheque porque se analiza una empresa con venta minorista a consumidores finales y su uso por parte de éstos no es habitual en la Argentina. Sin embargo, los costos del cobro mediante cheques se corresponden con los de transferencias en cuenta corriente.

de disponibilidad de los fondos en el momento y con operaciones al contado (excepto en el *link* de pago que admite tarjetas de crédito o Mercado Crédito).

Tabla 1. Tipos de medios electrónicos de pago y comisiones para el vendedor

	Descripción	Comisión
Bancario	Transferencias (TR)	0 %
	Tarjetas de débito (TD), acreditación en 48 horas.	0,9 %
	Tarjetas de crédito (TC) en 1 cuota, acreditación: 10 días hábiles (máximo).	2 %
No bancario	*Link* o botón de pago (LP) enviado por aplicaciones de mensajería, redes sociales o insertos en una web.	5,99 %
	POS móvil o POINT (PO): transferencias iniciadas por medio del deslizamiento de una tarjeta por un dispositivo lector que se conecta al celular.	3,49 %
	Códigos QR (QR): pagos mediante el escaneo de un código QR desde una billetera electrónica en el celular.	0,6 %
	Envío dinero (ED) a través de una billetera electrónica.	0 %

Fuente: Datos de BCRA [20] y Mercado Pago [21]

Tabla 2. Parámetros tributarios

	RI	MT
IG	30 % sobre el resultado después de intereses y amortizaciones	Impuesto integrado (categoría según ingresos anuales): 5.392,44 (H:1.739.493,79); 10.220,77 (J: 2.348.316,62); 11.741, 58 (K: 2.609.240,69)
IIBB	1,5 % sobre ventas netas	
Tasa SH	0,59 % sobre ventas netas	
IDCB	0,06 % sobre movimientos en cuenta corriente bancaria	
	Pago a cuenta IG	No es computable como pago a cuenta
Retenciones	IIBB: tarjeta crédito 1 %, medios no bancarios 0,5 %. IIBB bancarias: 1,5 %	

Fuente: datos obtenidos de AFIP [13], ARBA [22], Municipalidad de Bahía Blanca [23].

En función a la actividad definida, la empresa resulta alcanzada por los tributos y regímenes de retención exhibidos en la Tabla 2 que varían en función a su calidad tributaria. En el RI no se considera el IVA por tratarse de un tributo trasladable a consumidores finales, mientras que en el MT dicho impuesto (21 %) se adiciona a los gastos dada su imposibilidad de traslación. La alícuota del impuesto a los Ingresos Brutos (IIBB) comprende las actividades de producción de bienes listadas en el inciso D del código fiscal 2020 de la provincia de Buenos Aires; mientras que la tasa por inspección de Seguridad e Higiene (SH) representa la moda del rubro 31 de la ordenanza fiscal de Bahía Blanca (industrias manufactureras de productos alimenticios, bebidas y tabacos). El Impuesto a los Débitos y Créditos Bancarios (IDCB) se calcula en 1,2 % considerando que comprende tanto la recepción de los fondos (crédito) como su uso (débito). Las alícuotas de retención se seleccionan considerando una categoría de riesgo fiscal e incumplimiento medio. Como se explica en el marco de antecedentes, si bien las retenciones son un crédito impositivo implican un costo financiero por los fondos inmovilizados que se calcula tomando el promedio de la tasa Badlar diaria para el primer semestre de 2020 (28,7973 %) [20] y un lapso medio de inmovilización de 15 días al mes. El mismo tratamiento se aplica para el IDCB cobrado a los RI que se computan contra los anticipos mensuales del IG, suponiendo que la empresa cuenta con el certificado

MiPyME. A fin de simplificar el análisis, no se incluyen los costos asociados al sistema previsional: pago de autónomos en RI y aportes jubilatorios del MT.

Los valores de alícuotas impositivas, gastos de comisión, y demás datos son los vigentes durante el año 2020 y son netos de IVA. Además de los parámetros mencionados, el modelo considera los siguientes supuestos. La empresa:

a) tiene un nivel de ventas máximo en efectivo de $175.000 en MT y $ 315.000 en RI y solo puede aumentarlo empleando medios de pago electrónico (en casos de operaciones *online* los costos de envío y *packaging* están a cargo del comprador);
b) cobra el 100 % de las ventas bajo la modalidad indicada en cada caso, es decir, no hay combinación de diferentes medios de pago;
c) presenta un margen de ganancias sobre ventas del 60 %, calculado con el resultado antes de costos comerciales por modalidad de pago e impuestos;
d) tiene capacidad instalada ociosa por lo que puede aumentar sus ventas sin incremento de costos fijos, solo cambian los variables;
e) se financia únicamente con fondos propios: no hay intereses por deuda por solventar capital de trabajo;
f) exhibe unidad de administración y propiedad, lo cual implica que los beneficios y costos de la evasión recaen sobre la misma persona.

4 Resultados

4.1 Resultados descriptivos

Las tablas 3 y 4 exponen las estimaciones de costos y rentabilidades para cada medio de pago por tipología tributaria. Las estimaciones muestran que, para ambos sujetos tributarios, los **costos de los medios de pago** son nulos en el caso de efectivo, transferencia a caja de ahorro (CA) y envío de dinero mediante billeteras electrónicas (BE); y alcanzan su máximo cuando se trata del *link* de pago. El ordenamiento de las formas de pago en función a su costo encuentra a las transferencias en cuenta corriente (CC), códigos QR y tarjetas de débito como las menos costosas, y continúa con las tarjetas de crédito y el *point*. Si bien dicho ranking es independiente de la tipología tributaria, en términos relativos los costos son mayores para el MT, dada su imposibilidad de trasladar el IVA de gastos y comisiones.

Además de los valores, es interesante analizar la diferencia en cantidad y tipo de ítems que componen el costo según se trate de medios bancarios o billeteras virtuales. Estas últimas sólo contienen comisiones variables, a diferencia de los primeros que también incorporan cargos fijos mensuales por mantenimiento de cuenta o alquiler de equipos. La distinción es importante en el caso de emprendimientos que adoptan un medio de pago electrónico no para atender la demanda comercial, sino para cumplimentar una obligación formal. Si este fuera el caso, para ciertos niveles de venta resulta más rentable optar por un *point*, por ejemplo, respecto a una terminal POS.

Respecto a los **costos impositivos,** para el caso del RI representan un 19,64 % de las ventas (en promedio para los diferentes medios de pago), con valores mínimos de 18,31 % en el *link* de pagos y máximos de 20,11 % en las transferencias a CA y envío de dinero. El menor costo tributario en las modalidades con mayores costos obedece al

efecto de deducción de gastos financieros en la base imposible del IG. En el caso del MT, el costo impositivo medio asciende a 8,28 %, oscilando entre 7,93 % (efectivo) y 9,17 % (tarjeta de crédito en CC) y la moda en 7,95 %. Para el MT, las modalidades bancarias asociadas a CC son las que implican un mayor costo tributario porque el IDCB representa un gasto, a diferencia del RI que lo computa como un crédito. Por ello, excepto que utilicen cheques en su operatoria financiera, los MT debieran desestimar el uso de CC o reemplazarlas por CA para evitar el cargo por IDCB. De todas formas, los contribuyentes del régimen simplificado también cuentan con la posibilidad de solicitar reducción de alícuotas de dicho impuesto.

Tanto para el RI como para el MT, los costos tributarios incluyen el efecto de las retenciones de IIBB efectuadas por quienes acreditan los fondos que, si bien son un crédito impositivo, se incluyen pues implican un resultado negativo generado por la inmovilización de los importes retenidos. Incluso tales costos pueden ser mayores que los estimados, en los supuestos de empresas que tienen saldos impositivos a favor (por lo que no hay deuda contra la cual computar el crédito y por ende es mayor el plazo de indisponibilidad de los fondos) o no categorizan como mypymes (estando sujetas adicionalmente a regímenes de retención de IVA e IG).

En especial, los resultados del ítem tributario muestran la notable diferencia de onerosidad entre el régimen general y el simplificado: los costos impositivos para el MT representan menos de la mitad que para el RI. Ello responde fundamentalmente a la estructura del IG: en el caso del RI es un porcentaje sobre el resultado después de intereses y amortizaciones; mientras que en el MT es un monto fijo por categoría de impuesto integrado (IG, IVA). Esas diferencias también se observan en el total de costos de medios de pago e impositivos por peso vendido para cada sujeto tributario.

En relación a la informalidad, se observan dos situaciones. Por un lado, en un análisis dentro de cada tipología tributaria, se tiene un efecto directo por subdeclaración de ventas en efectivo que reduce a la mitad los costos tributarios del RI (de 20,09 % a 10,46 %) y en poco menos de la mitad los del MT (de 7,93 % a 4,54%). Es decir, una subfacturación del 30 % de las ventas en efectivo (respecto a la declaración del 100 % por el mismo medio) genera un ahorro por evasión tributaria del 9,63 % y del 3,39 % de los ingresos en los RI y MT, respectivamente. Por otra parte, al comparar entre sujetos tributarios, se detecta un segundo efecto subyacente: el importante cambio de los costos impositivos para niveles de ingresos cercanos al punto de inflexión entre los regímenes incentiva la informalidad. Por ejemplo, si el MT bajo estudio incrementara sus ventas mensuales en más de $ 42.437 (un 24,25 %) quedaría categorizado como RI, con un aumento promedio del 11,36 % de sus costos impositivos. Es decir que incrementar su actividad en un 25 % aproximadamente, implicaría duplicar los costos tributarios por peso vendido (de 8,28 % a 19,64 %). En el mismo sentido, si el RI analizado -con un nivel de ventas mensual real de $ 315.000- subdeclarara más del 30,97 % de sus ingresos quedaría encuadrado como MT, reduciendo casi a la mitad sus costos impositivos.

Tabla 3. Costos y resultados estimados para la microempresa adherida al régimen tributario general

CASO BASE RESPONSABLE INSCRIPTO	Efectivo 30 % subdeclaración	Efectivo	Medios de pago electrónicos										Promedio medios de pago
			Bancarios - cuenta corriente (cc)			Bancarios - caja de ahorro (ca)			No bancarios (billeteras virtuales)				
			Transferencia	T. Débito	T. Crédito	Transferencia	T. Débito	T. Crédito	*Link* de pago	*Point*	Código QR	Envío dinero	
	EF-sub	EF	TR-cc	TD-cc	TC-cc	TR-ca	TD-ca	TC-ca	LP	PO	QR	ED	
Ventas mensuales	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	
Costos	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	
Resultado antes costos medio pago y tributos	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	
Costos medios de pago													
Comisión (% sobre ventas)	0	0	0	2.835	6.300	0	2.835	6.300	18.869	10.994	1.890	0	
Costo mantenimiento cuenta ($ fijo mensual)	0	0	559	559	559	0	0	0	0	0	0	0	
Alquiler terminal POS ($ fijo mensual)	0	0	0	880	880	0	880	880	0	0	0	0	
Costos medios de pago ($)	**0**	**0**	**559**	**4.274**	**7.739**	**0**	**3.715**	**7.180**	**18.869**	**10.994**	**1.890**	**0**	**5.020**
Costos medio de pago (% ventas)	0,00%	0,00%	0,18%	1,36%	2,46%	0,00%	1,18%	2,28%	5,99%	3,49%	0,60%	0,00%	1,59%
Resultado antes de tributos	189.000	189.000	188.441	184.726	181.261	189.000	185.285	181.820	170.132	178.007	187.110	189.000	
Costos tributarios													
Impuesto a las ganancias (IG)	28.350	56.700	56.532	55.418	54.378	56.700	55.586	54.546	51.039	53.402	56.133	56.700	
Ingresos brutos (IIBB)	3.308	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	
Tasa por inspección seguridad e higiene (SH)	1.301	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	
Costo financiero inmovilización retenciones (*)	0	0	102	102	159	57	57	113	57	57	57	57	
Costos tributarios ($)	**32.958**	**63.284**	**63.218**	**62.103**	**61.121**	**63.340**	**62.226**	**61.243**	**57.680**	**60.042**	**62.773**	**63.340**	**61.852**
Costos tributarios (% ventas)	10,46%	20,09%	20,07%	19,72%	19,40%	20,11%	19,75%	19,44%	18,31%	19,06%	19,93%	20,11%	19,64%
Costos medios de pago y tributarios ($)	**32.958**	**63.284**	**63.777**	**66.377**	**68.860**	**63.340**	**65.941**	**68.423**	**76.548**	**71.036**	**64.663**	**63.340**	**66.872**
Costos medios de pago y tributarios (% ventas)	10,46%	20,09%	20,25%	21,07%	21,86%	20,11%	20,93%	21,72%	24,30%	22,55%	20,53%	20,11%	21,23%
Resultado neto ($)	**156.042**	**125.717**	**125.223**	**122.623**	**120.140**	**125.660**	**123.059**	**120.577**	**112.452**	**117.964**	**124.337**	**125.660**	**122.128**
Resultado neto (% ventas)	49,54%	39,91%	39,75%	38,93%	38,14%	39,89%	39,07%	38,28%	35,70%	37,45%	39,47%	39,89%	38,77%
(*) Costo financiero inmovilización retenciones													
Impuesto a los débitos y créditos bancarios	0	0	3.780	3.780	3.780	0	0	0	0	0	0	0	
Retenciones de IIBB	0	0	0	0	4.725	0	0	4.725	4.725	4.725	4.725	4.725	
Retenciones bancarias IIBB	0	0	4.725	4.725	4.725	4.725	4.725	4.725	0	0	0	0	
Total fondos inmovilizados	*0*	*0*	*8.505*	*8.505*	*13.230*	*4.725*	*4.725*	*9.450*	*4.725*	*4.725*	*4.725*	*4.725*	
Costo financiero inmovilización retenciones	**0**	**0**	**102**	**102**	**159**	**57**	**57**	**113**	**57**	**57**	**57**	**57**	
Nota. Las celdas coloreadas indican valores extremos:	mínimo	máximo											

Fuente: elaboración propia

Tabla 4. Costos y resultados estimados para la microempresa adherida al régimen tributario simplificado

CASO BASE RESPONSABLE INSCRIPTO	Efectivo 30 % subdeclaración	Efectivo	Medios de pago electrónicos										Promedio medios de pago
			Bancarios - cuenta corriente (cc)			Bancarios - caja de ahorro (ca)			No bancarios (billeteras virtuales)				
			Transferencia	T. Débito	T. Crédito	Transferencia	T. Débito	T. Crédito	*Link* de pago	*Point*	Código QR	Envío dinero	
	EF-sub	EF	TR-cc	TD-cc	TC-cc	TR-ca	TD-ca	TC-ca	LP	PO	QR	ED	
Ventas mensuales	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	**315.000**	
Costos	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	126.000	
Resultado antes costos medio pago y tributos	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	189.000	
Costos medios de pago													
Comisión (% sobre ventas)	0	0	0	2.835	6.300	0	2.835	6.300	18.869	10.994	1.890	0	
Costo mantenimiento cuenta ($ fijo mensual)	0	0	559	559	559	0	0	0	0	0	0	0	
Alquiler terminal POS ($ fijo mensual)	0	0	0	880	880	0	880	880	0	0	0	0	
Costos medios de pago ($)	**0**	**0**	**559**	**4.274**	**7.739**	**0**	**3.715**	**7.180**	**18.869**	**10.994**	**1.890**	**0**	**5.020**
Costos medio de pago (% ventas)	0,00%	0,00%	0,18%	1,36%	2,46%	0,00%	1,18%	2,28%	5,99%	3,49%	0,60%	0,00%	1,59%
Resultado antes de tributos	189.000	189.000	188.441	184.726	181.261	189.000	185.285	181.820	170.132	178.007	187.110	189.000	
Costos tributarios													
Impuesto a las ganancias (IG)	28.350	56.700	56.532	55.418	54.378	56.700	55.586	54.546	51.039	53.402	56.133	56.700	
Ingresos brutos (IIBB)	3.308	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	4.725	
Tasa por inspección seguridad e higiene (SH)	1.301	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	1.859	
Costo financiero inmovilización retenciones (*)	0	0	102	102	159	57	57	113	57	57	57	57	
Costos tributarios ($)	**32.958**	**63.284**	**63.218**	**62.103**	**61.121**	**63.340**	**62.226**	**61.243**	**57.680**	**60.042**	**62.773**	**63.340**	**61.852**
Costos tributarios (% ventas)	10,46%	20,09%	20,07%	19,72%	19,40%	20,11%	19,75%	19,44%	18,31%	19,06%	19,93%	20,11%	19,64%
Costos medios de pago y tributarios ($)	**32.958**	**63.284**	**63.777**	**66.377**	**68.860**	**63.340**	**65.941**	**68.423**	**76.548**	**71.036**	**64.663**	**63.340**	**66.872**
Costos medios de pago y tributarios (% ventas)	10,46%	20,09%	20,25%	21,07%	21,86%	20,11%	20,93%	21,72%	24,30%	22,55%	20,53%	20,11%	21,23%
Resultado neto ($)	**156.042**	**125.717**	**125.223**	**122.623**	**120.140**	**125.660**	**123.059**	**120.577**	**112.452**	**117.964**	**124.337**	**125.660**	**122.128**
Resultado neto (% ventas)	49,54%	39,91%	39,75%	38,93%	38,14%	39,89%	39,07%	38,28%	35,70%	37,45%	39,47%	39,89%	38,77%
(*) Costo financiero inmovilización retenciones													
Impuesto a los débitos y créditos bancarios	0	0	3.780	3.780	3.780	0	0	0	0	0	0	0	
Retenciones de IIBB	0	0	0	0	4.725	0	0	4.725	4.725	4.725	4.725	4.725	
Retenciones bancarias IIBB	0	0	4.725	4.725	4.725	4.725	4.725	4.725	0	0	0	0	
Total fondos inmovilizados	*0*	*0*	*8.505*	*8.505*	*13.230*	*4.725*	*4.725*	*9.450*	*4.725*	*4.725*	*4.725*	*4.725*	
Costo financiero inmovilización retenciones	**0**	**0**	**102**	**102**	**159**	**57**	**57**	**113**	**57**	**57**	**57**	**57**	

Nota. Las celdas coloreadas indican valores extremos: mínimo máximo

Fuente: elaboración propia

4.2 Análisis de sensibilidad

La tabla 5 y la Fig. 1 muestran los resultados de los análisis de sensibilidad realizados. Los hallazgos para el S1 confirman los resultados descriptivos sobre los costos de los medios pagos. El *link* de pago es la alternativa más costosa y por ende requiere un mayor incremento de ventas para cubrir los costos asociados (11,80 % y 16,06 %, RI y MT en ese orden). Por su parte, la transferencia a CA y el envío de dinero -al ser las modalidades de menor costo- implican un escaso aumento de la actividad para afrontar su implementación (0,05 % y 0,03 %, RI y MT, respectivamente), que solo responde a cubrir el costo financiero por inmovilización de las retenciones. Estos resultados, junto con el ordenamiento de los medios de pago según S1, son semejantes para ambas categorías tributarias. Sin embargo, por la imposibilidad de trasladar el IVA de los gastos financieros, los coeficientes de sensibilidad resultan mayores en el MT, es decir, el RI necesita un menor incremento en las ventas para cubrir el costo de cada medio de pago (columnas celestes –S1 RI- son menores que las naranja claro –S1 MT- en Fig. 1).

Los valores mínimos y máximos de S2 (alto total de columnas en Fig. 1) corresponden a los mismos medios de pago identificados según S1, al igual que su ordenamiento. Sin embargo, en este caso, es interesante comparar los valores de S2 entre categorías tributarias (columnas azuladas versus anaranjadas en Fig. 1): los niveles de aumento de ventas que necesita el RI para cubrir los costos del medio de pago y el beneficio fiscal por evasión son sustancialmente superiores a los del MT. Incluso, las modalidades más económicas (transferencias bancarias, envío de dinero, tarjetas de débito vinculadas a CA o códigos QR) implican para el RI un aumento de facturación mensual que triplica el requerido para el MT; mientras que para las restantes alternativas ese incremento es del doble entre RI y MT (tarjetas de crédito, *point* y *link* de pago). La diferencia de S2 entre RI y MT es más alta en los medios de pagos menos costosos por el efecto del componente impositivo: es mayor el impuesto porque existen menos gastos deducibles de la base imponible del IG, entonces es menor el resultado neto y por ende se requiere un mayor incremento de ventas.

Tabla 5. Sensibilidades por categoría tributaria y medio electrónico de pago

Medios de pago		TR-cc	TD-cc	TC-cc	TR-ca	TD-ca	TC-ca	LP	PO	QR	ED
S1	RI	0,39%	2,50%	4,60%	0,05%	2,15%	4,24%	11,80%	6,57%	1,11%	0,05%
	MT	2,83%	5,94%	8,57%	0,03%	2,68%	5,53%	16,06%	7,90%	1,30%	0,03%
	RI respecto a MT	-2,44%	-3,44%	-3,97%	0,01%	-0,53%	-1,29%	-4,27%	-1,33%	-0,19%	0,01%
S2	RI	24,53%	27,03%	29,63%	24,18%	26,67%	29,26%	38,76%	32,28%	25,50%	24,18%
	MT	8,80%	13,59%	16,42%	5,88%	8,62%	13,20%	22,75%	15,83%	7,22%	5,88%
	RI respecto a MT	15,73%	13,44%	13,22%	18,30%	18,05%	16,06%	16,01%	16,45%	18,27%	18,30%
S3	RI	24,14%	24,53%	25,03%	24,13%	24,52%	25,02%	26,97%	25,71%	24,39%	24,13%
	MT	5,97%	7,65%	7,84%	5,85%	5,94%	7,67%	6,69%	7,93%	5,92%	5,85%
	RI respecto a MT	18,17%	16,88%	17,19%	18,28%	18,58%	17,35%	20,28%	17,78%	18,47%	18,28%

Nota. S1: incremento en ventas necesario para cubrir los costos asociados a la modalidad de pago y mantener el mismo resultado neto que cobrando 100 % en efectivo (sin evasión); S2: incremento en ventas necesario para cubrir los costos asociados a la modalidad de pago y mantener el mismo resultado neto que subdeclarando 30 % de las ventas en efectivo; S3= S2-S1 es el incremento en ventas necesario para cubrir solo los costos de la informalidad.

Fuente: elaboración propia

Por último, los valores de S3 expresan el incremento de ventas necesario para cubrir el ahorro fiscal "perdido" por la subdeclaración de ingresos que no posibilitan los medios de pago electrónicos, es decir, es el efecto puro de la evasión fiscal. Nuevamente los aumentos de actividad requeridos son más altos para los contribuyentes del régimen general. Este efecto diferencial de la informalidad para el RI respecto al MT, se refleja claramente en al comparar los tramos azules –S3 RI- y naranjas –S3 MT- de las columnas en la Fig. 1. La diferencia de magnitud entre tales secciones de las columnas muestra que el RI tiene muchos más incentivos a subdeclarar ingresos por los impuestos asociados linealmente al monto de ventas.

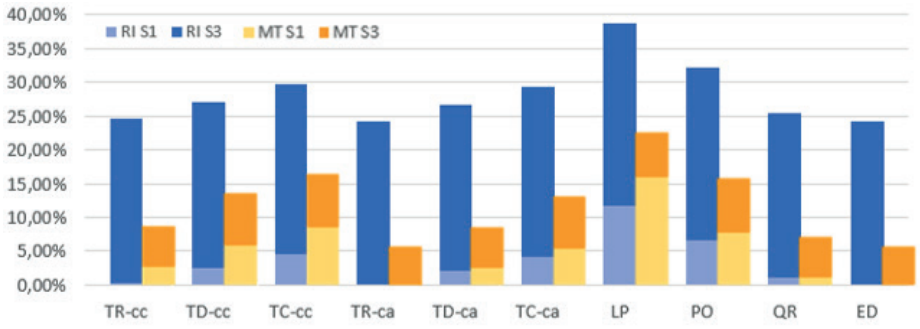

Fig. 1. Sensibilidades por categoría tributaria y medio electrónico de pago

5 Consideraciones finales

Además del efectivo, existen diversos medios electrónicos de pago cuyos costos son diferentes y, a su vez, impactan de forma disímil según la categoría tributaria de la empresa. En un esfuerzo por clarificar la relación entre modalidades digitales de pago, tributos e informalidad, a partir de un caso de estudio simulado, este trabajo compara los resultados asociados a 11 medios de pago para dos tipos tributarios (RI y MT), analizando la incidencia de la subdeclaración de ingresos sobre operaciones en efectivo.

Según los hallazgos, el ordenamiento de los medios de pago por su costo no varía entre RI y MT, aunque en términos relativos son mayores para el MT. El efectivo, el envío de dinero mediante billeteras virtuales y las transferencias a CA son los más económicos; mientras que las tarjetas de crédito, el *point* y el *link* de pago resultan los más onerosos. Asimismo, se destaca la importancia de conocer y evaluar la composición de los costos de medios bancarios y no bancarios a la luz de la organización del negocio y las disposiciones normativas vigentes a fin de seleccionar el más conveniente.

Analizando la onerosidad de los medios electrónicos de pago respecto al incremento de uso en el contexto de pandemia, se observa una tendencia al empleo de alternativas menos costosas (tarjetas de débito, transferencia, tarjetas de crédito, Mercado Pago [16]). Una excepción a esto es el *link* de pago por ser la modalidad de cobro que más creció en la plataforma [19] y en este estudio se reporta como la de mayor costo. Ello puede justificarse en que gran parte de las operaciones durante el ASPO fueron *online*, donde no existe la posibilidad de uso del *point* y el *link* resulta más cómodo frente a

otras opciones como el envío de un código QR. Sin embargo, su mayor uso también puede atribuirse a un desconocimiento de los vendedores de su costo.

Respecto los costos impositivos, la situación se invierte siendo mayores para el RI. En ese caso por la estructura del régimen, con porcentajes de IG vinculados a resultados, los medios de pago menos costosos derivan en mayores costos impositivos. Para el MT, las modalidades bancarias asociadas a CC son las que generan un impuesto más elevado, en especial por la imposibilidad de computar el IDCB como pago a cuenta de obligaciones fiscales.

En relación a la informalidad, el efecto directo muestra que una subdeclaración de 30 % de las ventas en efectivo reduce los costos tributarios en 9,63 % para el RI y en 3,39 % para el MT. Es decir, cuantitativamente y en términos relativos, los incentivos a evadir son mayores para el RI. Por su parte, el efecto subyacente indica la existencia de estímulos a subfacturar en niveles de ingresos cercanos al punto de inflexión entre los regímenes tributarios, evitando un cambio brusco en los costos por impuestos.

Todos los resultados descriptivos comentados, son confirmados y refinados por los hallazgos del análisis de sensibilidad: los incrementos de ventas necesarios para solventar los costos de los medios electrónicos de pago son mayores en el MT (S1), mientras que los incrementos de actividad requeridos para cubrir los gastos de modalidad digitales y el ahorro fiscal por subdeclaración son más altos en el RI (S2). Esto marca nuevamente la onerosidad del régimen general con su consecuente incentivo a mayor subfacturación. Incluso, analizando S3 respecto a S2 (Fig. 1), los resultados indican que el principal limitante a la adopción de medios de pago electrónicos en empresas pequeñas está mayormente asociado a la informalidad y no a los costos de transacción.

A nivel teórico, el estudio presentado contribuye a profundizar la comprensión del fenómeno de la evasión tributaria y el nivel de adherencia a los medios electrónicos de pago, colaborando con el diseño de políticas públicas tendientes a reducir la informalidad empresarial e incrementar la inclusión financiera en un contexto donde tales tópicos representan problemáticas actuales. Por ejemplo, podría pensarse en exenciones de IVA a MT sobre las comisiones por cobros electrónicos que desincentiven la informalidad y beneficien al Estado generando un potencial incremento de la recaudación fiscal. Desde el punto de vista práctico, los resultados del artículo resultan de interés para empresarios al momento de evaluar los efectos asociados a diferentes medios de pago.

Los hallazgos del presente trabajo provienen de un estudio de caso y, por ende, no pueden ser generalizados a empresas con actividades diferentes, radicadas en otros distritos o no sujetas a los supuestos del modelo. Además de tales limitaciones, puede mencionarse la falta de consideración de otros costos y beneficios asociados al fenómeno pero no cuantificados. Dentro de las futuras líneas de investigaciones se pretende estudiar los incentivos de los contribuyentes a la informalidad en el punto de inflexión entre los regímenes tributarios.

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Building High Performance Teams

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Abstract. Work design is being constantly transformed by technology and requirements for polyvalent workers piloting the work system instead of operating it. Performance no longer depends exclusively on working hours, but in multiple aspects that balance the vision of production systems results. The purpose of this paper is to investigate self-management teams' implementation and its effects on performance. A Brazilian cosmetics company case study of team development was used as a guidance for this investigation and company performance reports were the data source for descriptive statistics and multivariate analysis. Boxplot performance analysis was applied over team building stages along with One-way Variance Analysis to test average performance differences among stages' transitions. Tukey test was sequentially applied to identify its statistic differences in pairs. Results revealed team development reached the expected performance over team stages. Forming to storming, though, was the only transition with no performance average gains. Storming to norming was the highest improvement, which meets literature principles. The present research is limited to a single sociotechnical environment and performance measurement is based on average data. Therefore, specific conclusions imply further research to extend findings to other contexts. However, the present study identified empowerment best practices to achieve superior performance. The originality of this paper consists on providing consistent connection between team development theory and practice, exploring sociotechnical approach benefits through practices into performance.

Keywords: Work organization, Team performance, Self-managed teams, Empowerment.

1 Introduction

Work rationalization, born in the Classical School with Scientific Administration, indorsed critical specification for task execution, and little flexibility in the work posts. Taylor's organizational model consisted of a rigid hierarchy, that it was highly dictating specialized and standardized tasks (Weisbord, 2011; Batiz-Lazo, 2019). The

social scientist Elton Mayo was the first to reveal opposition to this work system. Hawthorne Experience, coordinated by the sociologist between 1924 and 1933, showed that Western Electric Company's productivity increased with the stimulus of social aspects in the work environment. The School of Human Relations contradicted Taylor's theory since it knocked down the preponderance of physiologic factors on the psychological ones (Zoller and Muldoon, 2019). Toyota's Japanese approach also brought revolutions when they started to consider the intellectual prospect of working members as a critical success organizational factor (Simonetti and Marx, 2010).

The models that came after Taylorism started to value the collective work, inside of activities that before were only mechanists. They tried to bring together the projection with the execution of tasks previously segmented by the classical approach (Joullié, 2018). Autonomous teams, however, presented a differentiation factor: the minimization of the hierarchical role figure, stimulating teams for high performance (Marx, 1997). The sociotechnical model was discovered, and subsequently, studied by Tavistock Institute researchers after observing the productivity's optimization in the English coal mines through self-management in 1949 (Salerno, 1994; Moreira and Marx, 2008).

Lee and Edmondson (2017) recently investigated current trends and expected benefits that motivate the development of self-managing organizations. Less-hierarchical organizations with employee empowerment initiatives stimulate brighter and faster responses in dynamic conditions. Also, Yin *et al.* (2018) argue that empowerment has been a mechanism to reduce traditional managing costs and proposed an economic perspective to explain how empowerment practices affect organizational performance indirectly through moderating the effect of the employee-employer exchange relationship.

The work with greater autonomy can increase productivity and work motivation providing competitive advantage for organizations (Manz and Sims, 1996). The implantation of autonomous teams according to the sociotechnical model, however, involves great and challenging organizational changes (Salerno, 1994). The introduction of these teams requires a new style of leadership and designates greater responsibilities to workers, and not everyone is willing to work in teams. The implementation of these teams is usually of medium to long term and involves high costs, demanding deeper organizational changes and there is not always a consensus between the hierarchies for political changes (Marx, 1997; Cunningham and MacGregor, 2000). Moreover, autonomy degrees must be consistent with strategic goals (Olsson and Bosch, 2018).

Based on the problems related to the organizational challenges of this work model described above, the following research question is proposed for this paper: Can self-managed teams bring performance improvement? A case study is used as a guidance for this investigation. The case study's company introduced sociotechnical work teams willing to reach high performance and this paper explores its approach with performance improvement over team-building stages. Therefore, this paper presents a meaningful relationship between team empowerment theoretical principles and practice.

2 Literature review

This section explores theoretical background of teams in three dimensions considered relevant to this paper: team building, empowerment and team performance measurement.

2.1 Team Building

Widely known as an effective team building design for the educational setting (Riebe *et al*., 2010; Aydin and Gumus, 2016; Weber and Karman, 2017), Tuckman approach (1965) remains famous for team development model and it is still known for its four-sequential stages (Kur, 1996; Largent, 2016; Manges *et al*., 2017). Forming is the first interaction of team members, when they become familiar with each other and try to find out which behaviors are acceptable regarding their tasks, feeling confused on how to act and unsure about the benefits of team participation. There is suspicion, fear and anxiety on the onward work and the common goal supported by the formed team. At storming stage, members start to show resistance and hostility towards each other and conflicts are often caused by miscommunication, what may lead them to disbelief in the collective power. These problems begin to be solved at norming stage, when the whole team effectively learn how to work together and internal differences are overcome. The focus on tasks, interpersonal relationship and mutual identification among members are fortified. Finally, performing stage comes and the responsibility shared is intensified, together with creativity and the expected productivity. Mutual cooperation and team self-identity provide exceptional results (Tuckman, 1965).

Tuckman and Jensen (1977) formally extended the original model and added a fifth stage, adjourning, to provide opportunity for acknowledgements. Since then, the model was studied, applied and successfully validated in many team development fields, remaining strongly accepted (Largent, 2016; Aydin and Gumus, 2016; Manges *et al*., 2017). An Indonesian research has recently used Tuckman model as a theoretical reference to investigate virtual team performance of Binus University e-learning student's capability of solving teamwork problems (Siregar *et al.*, 2018).

Manges *et al*. (2017) successfully used the model in the healthcare environment as a guiding framework to improve safe patient care delivery. Nurse leaders' behaviors changed over Tuckman stages and were critical to build high performance teams. At the performing stage, nurse leaders no longer coordinated team actions and focused mainly on empowering members that developed shared leadership in the work design.

Kuhrmann and Munch (2016) highlights Tuckman theory's importance and argue that project managers must be familiar with the theoretical stages because they do not only start during project beginnings, but also when new members join team projects. The authors applied group dynamics with graduate students at Munich Technical University and Blekinge Institute of Technology and reinforced the premise that performance drops after changing teams. Conjointly, the dynamics revealed that time pressure, team size and missing strategies are the factors that mostly impact performance while task complexity and communication aspects affect work efficiency. Additionally, Largent (2016) reinforces Tuckman pattern that team's skill level rises

over time and team enthusiasm starts high, drops and then returns to a high level. The author also emphasized the importance of team ability to recognize the team current stage because this awareness can provide knowledge to understand team progress and distinguish between normal and abnormal difficulties along team development.

On the other hand, Tuckman's model was also challenged by some researchers. Kur (1996) complemented that company teams can possibly transit from one stage to another during work execution. Miller (2003) argued that complex teams do not follow the linear team building performance suggested by the psychologist researcher. Rickards and Moger (2000) also criticized the theoretical model, claiming that not all teams go through all stages. According to the authors, storming stages can possibly never end and teams become dysfunctional, failing to pass a weak behavioral barrier before norming. Even though most teams overcome the weak barrier, fewer teams pass the strong performance one and do not achieve exceptional performance.

A similar model of team development was additionally proposed by Katzenbach and Smith (1993), projecting a performance curve that losses up to the team complete formation, integration and alignment of the members. Therefore, formation phase will undoubtedly need more time than a group run by a single leader to reach a desirable performance. According to Katzenbach and Smith (1993) it happens because a real team demands more from its members and team formation phase tends to be less effective. Formation requires difficult adaptation periods in the level of sharing experiences and distinct knowledge among members can bring disagreements and competition. Learning requires trust, as well as trust promotes learning. Therefore, learning and trust are not earned in a short period and only over time inevitable conflicts are solved.

Staniforth (1996) claims that many organizational practices and systems are more aligned to individuals, which inhibits team maturity growth and consequently teamwork performance. Castka *et al*. (2001) grouped successful factors of high performance teams implementation into two categories and seven subgroup categories: I) system factors: organizational impact; alignment and interaction with external entities; performance measures and defined focus II) human factors: knowledge and skills, individual needs and group culture.

2.2 Empowerment

High performance companies depend on internal policies and capabilities (Okoshi *et al*., 2019). Empowerment practices allow coworkers to gather relevant information from each other and prompt employees to work as teammates, which reduces communication and coordination costs. Unlike ineffective authority, autonomy can lead self-managed teams with consistent knowledge shared to make better decisions, contributing to organizational performance and reducing monitoring high costs (Yin *et al*., 2018).

Idris *et al*. (2018) found empirical evidence that employee empowerment strengthens job satisfaction for Malaysian capital local workers. Potnuru *et al*. (2019) recently identified that organizational learning culture remarkably influences the relationships of team building and empowerment on employee competencies in Indian cement

manufacturing companies. Another interesting finding is the interrelationship between enabling management controls and staff empowerment and their mutual beneficial effects on performance in Australian companies (Baird *et al.*, 2018).

Jian'an (2008) discussed how to build self-management teams through empowerment, proposing pushing and pulling power strategies to achieve the desired dynamic equilibrium between supply and demand of power along team evolution. Empowerment advances gradually with time, maturity and experience, consequently benefits are only obtained in long-term. Strategic guidance is a requirement to optimize business performance through previously established autonomy levels that meets organizational specific ambitions (Olsson and Bosch, 2018). Autonomy degrees are often low during team forming stage and increases along team life cycle, exerting influence on outcomes (Hess, 2018).

Even though moving away from a traditional hierarchical design is a demand, most organizations persist to inhibit and limit employee's participation and empowerment skills and shifting responsibilities are impossible if leaders at every level are not truly committed to empower their subordinates (Huusko, 2006; Attaran and Nguyen, 2000; Horner, 1997).

According to Hess (2018) and Brower (1995), hierarchy must be limited to offer only guidelines as well as the confidence required to work execution and autonomous team members' expectations for top leader involvement must be aligned with previously established empowerment degrees consistently further reinforced to ensure perceptions that autonomy given is a real purpose and not purely symbolic.

In order to accelerate autonomy progress, empowerment practices must be adapted. Some approaches are commonly implied, such as training development plans for motivation and knowledge improvement, along with performance assessments connected to the organizational learning programs (Brower, 1995; Holt *et al.*, 2000; Potnuru *et al.*, 2019). Employees' strengths must be intensified instead of focusing on their weaknesses, because complementary team members' skills compensate individual flaws to achieve common goals (Margulies and Kleiner, 1995). In addition, clear goal statements through effective communication channels are meaningful. Targets and decisions must also be appraised by managers to ensure that commitment and efforts are focused on expected directions. Performance results, acknowledgments and rewards must be afforded not only to individuals, but also to the whole team, to reassure teammates take responsibility for each other's performance. (Brower, 1995; Elmuti, 1997; Conti and Kleiner, 1997). In conjunction with open and frequent communication, all-inclusive recruitment and consistent resource allocation are other preconditions to be granted to autonomous team members (Hess, 2018).

2.3 Team performance measurement

Teams with greater autonomy demand performance measurement indicators to appraise autonomy progress and results achieved over time (Marx, 1997). In order to build high performance teams, it is exceedingly indispensable that team members are acquainted and in total consonance with the chosen performance measurement system. According to Aguinis (2013), there are some fundamentals for team performance

assessment. Firstly, it is essential to ensure that teams are actually teams sharing common goals and not simply small groups with individual targets. Secondary steps are the investment in measurement structures and clear establishment of performance goals. Further, the selection of multiple appraisal methods focused on processes as well as outcomes and, finally, long-term changes are assessed.

Macbryde and Mendibil (2003) propose a four dimensional model for team performance measurement. I) team effectiveness, the dimension which process' results satisfy team stakeholders; II) team efficiency, the dimension in which internal processes support the achievement of process outcomes; III) learning and growth, which consists on monitoring team progress. Some features of this assessment involve transferable skills, documented learning, best practices, tools, methods, process improvement and team innovation potential; IV) satisfaction of the members, which implies motivation and personal fulfillment measurements, quantifying how teamwork contributes to the growth and personal well-being of each teammate.

Work designs, team composition and direct or indirect factors influencing high performance are widely explored by researches to support team cohesion theories (Ferreira *et al.*, 2012; Wilsher, 2015; Moura *et al.*, 2019). Rezvani *et al*. (2019) recently applied partial least square regression analysis on construction project teams' surveys to measure emotional intelligence relationship with team performance. Emotional intelligence and trust as a mediate factor were positively related to team performance, while conflict mediate factor presented a negative relation. The study implies that relationship conflicts could be diminished, and trust can be reinforced by improving emotional intelligence to reach performance enhancement. Cha *et al*. (2014) also used the same statistical methodology with developed surveys based on literature to support member's psychological proximity has a critical effect on team performance.

Jaca *et al*. (2013) applied a teamwork effectiveness measurement structured by survey to investigate key performance factors employing Input-Mediator-Outcome methodology (Ilgen *et al*., 2005; Mathieu *et al*., 2005). Independence, autonomy, internal leadership, conflict management were some common highly rated and constantly measured in healthcare and manufacturing distinct environments.

Team performance measurements have been also consistently worked out to test work designs involving leadership styles to evaluate optimizing performance structures. Ciasullo *et al*. (2017) measured effectiveness, efficiency and satisfaction of members dimensions to compare a traditional top-down with a hybrid bottom-up team building approach. The authors used not only lead-time, an organizational performance indicator, but also applied external and internal surveys to quantify both, customer and employee's satisfaction. Bottom-up team development performed better across all three dimensions of this integrated performance assessment. Yang and Choi (2009) also identified that empowerment elements influence on team performance through linear regression.

Han *et al*. (2017) have indirectly explored some dimensions suggested by Macbryde and Mendibil (2003) in a survey research, testing the effect of shared leadership on team perceived performance. Statistical analysis performed have supported shared leadership indirectly increases performance through stimulating knowledge share, commitment to goals and activity coordination as team mediate factors. Complemen-

tary, Müller *et al*. (2018) have also found that shared leadership positively affects team performance on a laboratory team decision-making exercise. Statistical analysis showed not only that sharing leadership brought quality improvement, but also perceived task complexity strengthens this effect. Even with constant complexity, when recognized as harder tasks, shared leadership was intensified and fewer errors were made in work execution.

3 Research Design

This paper presents a case study of team building, introduced by a cosmetics Brazilian company with the purpose to reach higher performance with the development of shop-floor self-managed teams. Empowerment practices with technical and behavioral trainings were provided to gradually achieve the desired team autonomy degrees over time. This research consists on measuring quantitative team performance over team building stages and evaluate the team development project, that was segmented by five learning levels. These five progressive stages structured by the company, presented by Figure 1, involved all factory teams and each level was planned to last the period of a year. Leadership left coordination role and gradually started to act as internal coachers and consultants, limiting to provide only generic directions along with confidence for members to accomplish autonomy. An important procedure followed by the company is that, for each stage advancement, besides the mandatory approval after trainings, auditing carried out to reassure that behavioral and professional improvement were successfully achieved to certify team breakthrough.

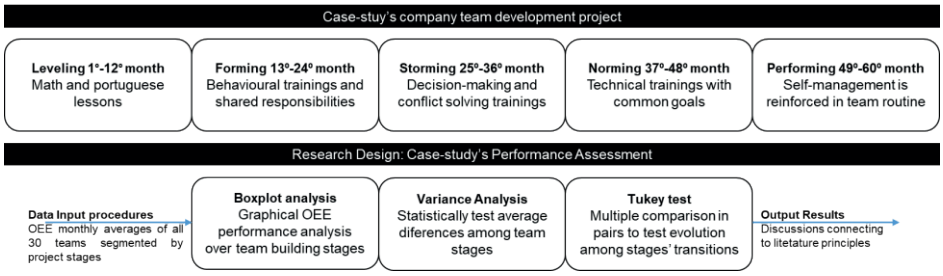

Figure 1. Research Design.

Quantitative performance reports provided by the company at the end of the project were the original data source for all the analyses. The main shop-floor performance indicator, overall efficiency, was chosen for the assessment. Overall line efficiency is measured through the formula Availability x Performance x Quality and team evaluation was applied by project consultants and team leaders. This indicator considers three percentage target dimensions, which only good parts are produced (100% quality), at the maximum cycle time speed (100% performance), and without equipment interruption (100% availability). Since the purpose is generic conclusions, team performance data of all 30 developed teams, were converted to monthly performance averages as a single team for all the following analyses described below.

1. Boxplot with all stages of overall efficiency's performance in a single chart was applied to graphically analyze performance over team learning stages.
2. One-way variance analysis was applied to statistically test performance average differences among team stages.
3. Tukey test was applied to test overall efficiency's multiple comparison in pairs to test performance evolution analysis between stages' transitions.

The performance assessment exhibited by Figure 1 was applied in academic environment to evaluate performance enhancement with the new intended work design and consequently answer the research proposed question regarding the ability of self-managing teams to bring high performance.

4 Results

Overall efficiency exhibits wide-ranging performance evolution over the stages, presented by Figure 2. It is perceptible forming to storming is the only particular distinguishable transition that did not present considerable difference in the average values. Performance staunchly had its greatest increase at storming to norming and repeatedly had another breakthrough at performing stage, when overall efficiency data is more concentrated, reaching persistent performance stability.

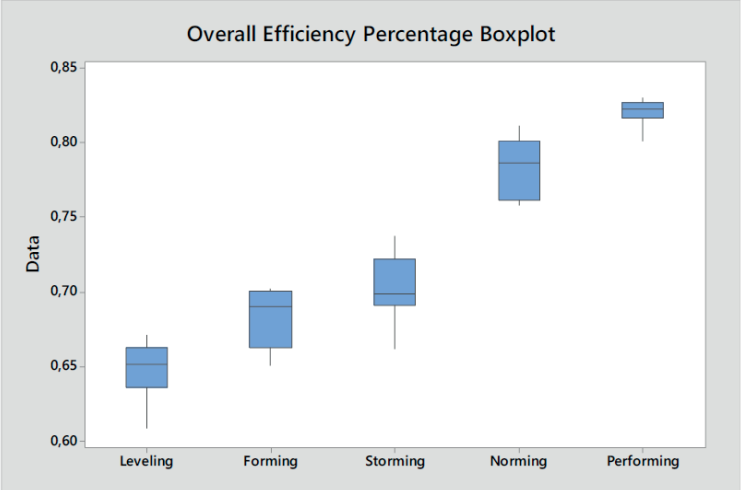

Figure 2. Boxplot analysis.

Performance behavior presented in boxplot reinforces some literature principles further explored in discussion section. Boxplot method provided graphical evolution overview, summarizing each stage's enhancement along team development. A single-factor variance analysis for overall efficiency was sequentially appropriate to test significant average difference among stages. Table 1 details the hypothesis test, performed with 95% confidence interval for this analysis.

Table 1. Hypothesis test.

Method	
Null hypothesis	All Means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0,05
Equal variances were assumed for the analysis.	

Factor Information		
Factor	Levels	Values
Factor	5	Leveling; Forming; Storming; Norming; Performing

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	4	0,24884	0,062210	184,25	0,000
Error	55	0,01857	0,000338		
Total	59	0,26741			

Before conclusions, test premises were challenged. Since residues showed a large adherence to the standard normal distribution and residual variances were approximately equal, premises were ratified. Considering a 95% confidence level, H0 was rejected, since p-value < 0.05. Therefore, statistical evidence of significant average difference for at least a couple of overall efficiency's stages was found. Tukey's test was then conveniently useful to test average differences between stages in pairs, presented by Figure 3.

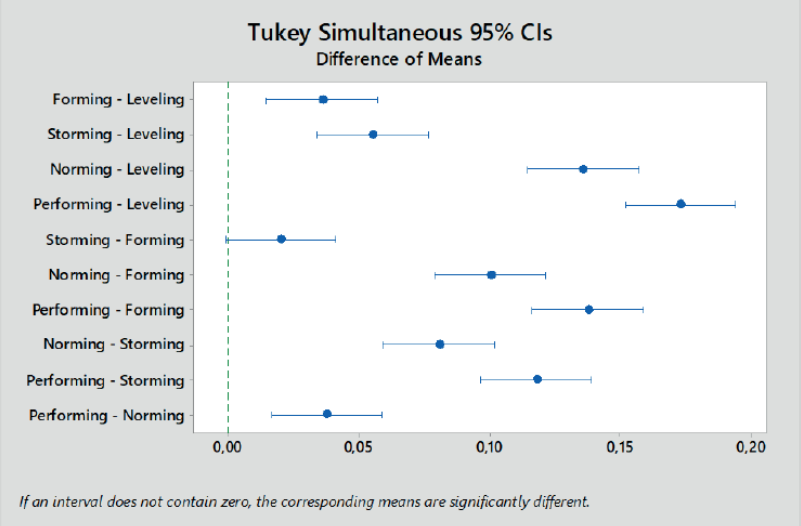

Figure 3. Tukey test.

By means of the 95% confidence interval for differences between averages, Tukey's test showed that only forming to storming stage had no significant difference, as

suspected upon boxplots descriptive analysis. In addition, it also implied a respective improvement for all the other transitions compared in pairs since the difference is always positive, hence, it essentially diagnoses overall efficiency gain over all other transitions, except forming-storming.

5 Discussion

The training development approach adopted by the company to introduce team development matches Tuckman's initial model (1965). The autonomy given was previously planned to attend organizational demands as highlighted in literature by Olsson and Bosch (2018) and autonomy was initially low (Hess, 2018). Both initial Boxplot and Variance Analysis approaches imply performance improvement along team autonomy progress.

Boxplot presented consistent performance breakthrough over team development, even though some stage transitions noticeably had different improvement scales. Although there was no performance loss from forming to storming as defended by theory (Tuckman, 1965; Katzenbach and Smith, 1993), it was the only transition with no performance average gains since Tukey's test showed no significant average differences between both stages. Storming to norming is highlighted by Tuckman theory as the greatest performance evolution, which also coincides with the case study's pattern. The highest improvement also corresponds to Katzenbach and Smith's theory (1993), that implies a huge evolution from potential team to real team. Tukey's test analysis also implies that teams have succeeded at passing both, weak behavioral and strong performance barriers, suggested by Rickards and Moger (2000).

Salerno (1994), Manz and Sims (1996), and Simonetti and Marx (2010) emphasized that self-managed teams, besides performance gains and commitment improvement, also reduces processes variability, which was an achieved result by the teams, since performing stage presented consistent lower variability in Boxplot analysis.

Learning and growth and team efficiency are some of the dimensions suggested by Macbryde and Mendibil (2003) related and explored in this case study. Team development brought the high performance expectation achievement in the long-term defended by sociotechnical researchers (Moreira and Marx, 2008). It is essential to recognize that empowerment practices applied are related to theoretical principles, such as training programs, open communication and shared leadership with previously designed individual responsibilities (Brower, 1995; Margulies and Kleiner, 1995; Hess, 2018).

This study also implies theoretical discussion related to future approaches of organizational work. Salerno (1994) defends that despite the autonomy given for decision-making during work execution, teams cannot be regarded as completely autonomous, after all even with great empowerment, members can't be completely independent since they belong to an organization with strategies of its own. However, Zarifian (1997) believes that this tends to change in the future, because according to the author, it is not possible to keep two management systems built on different principles for too long. Self-organizations do not only reduces coordination costs (Yin *et*

al., 2018) but remain studied because they also respond more effectively in dynamic scenarios (Lee and Edmondson, 2017).

This paper supports sociotechnical approach principles, bringing evidence that the case study's company achieved its ambition to reach high performance with the new work design with empowered teams (Salerno, 1994; Marx, 1997). Empowerment benefits remarkably appeared in the long-term, as implied by researchers (Jian'an, 2008; Olsson and Bosch, 2018). This study suggests that a team building prosperity has a connection to empowerment practices that meets literature suggestions (Margulies and Kleiner, 1995; Elmuti, 1997; Brower, 1995) such as internal alignment between managers and teams (Hess, 2018) and proper strategic guidance before team development to gradually introduce autonomy (Olsson and Bosch, 2018).

6 Conclusion

This paper strengthens the hypothesis that self-managed teams can reach high performance, since quantitative analysis showed performance evolution on the presented case study, and positively answered the research investigative proposed question. Team building academic contributors and sociotechnical researchers provided a strong theoretical background, making it possible to connect theory to practice identifying similarities and divergences shown in the discussion section. The consistency of this integration brings relevance and originality to this paper in work organizational field.

Limitations are also relevant to direct following research to cover some topics left unexplored in the present case study. For this reason, cost-exchange perspective must be a further study, to quantify managing costs reduction brought by empowerment practices defended by literature and examine the investment made on training programs comparing to team development's cost reduction. It is equally important to emphasize that we do not generalize and extend our conclusions to other realities because the present study was restricted to a single company case-study.

This paper focused on measuring team performance across team development, exploring learning and growth versus team efficiency dimensions. The unexplored dimensions could be further assessed by internal surveys to measure employee's satisfaction individually and inside their own teams, together with external surveys to evaluate customer satisfaction, as explored by team building research present in the visited literature. Complimentarily, empowerment measurement itself through external questionnaires along with internal learning and shared leadership mediate factors' influence on performance could be meaningful techniques to extend our case study's analysis.

Statistical analysis presented in research design were applied using team performance averages for general conclusions. Consequently, a further study exploring teams individually could also contribute to additional and more specific studies. It is also suggested the Myers-Briggs Type Indicator test application for team building and leadership development. Based on the ideas of analytical psychology, the test provides individual personality analysis and their behavior in different situations, consid-

ering specific preferences, values and motivations. Therefore, another complementary research involving members' personalities inside teams could be also an interesting following theme to test relations between team personality structure and performance.

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Human Resources 4.0: Use of Sociometric Badges to Measure Communication Patterns

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Abstract

Teams are fundamental for innovation and efficient communication may be fundamental for team performance. The aim of this paper is to present the use of sociometric badges in real workplace teams to display how team structure communication patterns can be measured and analyzed. The selected method consists of four case studies of different organizations, where the unit of analysis is represented by a meeting team. Use of this emergent technology allowed the evaluation of vocalization distribution, turn taking frequency and overlapping speech metrics. Main results of the analysis showed that team vocalization tenure corresponds to performance results but vocalization distribution does not, which was unexpected. We found where the average speech segment was high, the meeting overcome the 100% of team vocalization tenure, and the total overlap time was also high. We identified different kinds of overlapping speech. Higher overlapping seems to occur more frequently when total overlap time is high but dominance is low than when total overlap and dominance are both high. Badges metrics also allowed a preliminary identification of three meeting stages. Finally, we identified possible future research lines.

Keywords: sociometric badges, team interaction, emergent technologies, human resources, innovation.

1 Introduction

Changes over the last three decades have been highly accelerated owing to the advent of technology and innovations in communications [1] so the role of technology in contemporary organizations plays an increasingly important place [2]. Organizations are called to adapt in order to stand effective, productive and competitive in a volatile, uncertain, complex and ambiguous environment. In this process, a vital feature of modern organizations is working under changing circumstances; they increasingly adopt

work teams to coordinate activities [3]. In particular, the development and introduction of innovations in an Industry 4.0 manufacturing environment poses some challenges to human resource management. Industry 4.0 require interdisciplinary project teams [4].

As teams became a common working unit for managing change [5], investigating teams in order to understand team communication patterns is essential. Similarly, comprehension of the collaboration dynamic is becoming more and more important to improve team performance. The role of teams is fundamental for innovation. One of the competences that may enhance innovation processes is communication, understood as creating fluid communication pathways [6]. However, while digital communication is important in the modern workplace, face-to-face interaction still represents a large and important share of organizational communication, information exchange, socialization and informal coordination [7].

Currently, a variety of devices and technologies are used for business administration as a way to guarantee that processes are producing the expected results [8]. Specifically, electronic devices can measure communication patterns among teams [9-14]. For example, it has been argued that a balanced vocalization in between team members can be considered as a good proxy in relation to team performance [12, 13]. Despite these advances mean enormous potential for the strategic role of human resources function [1], there is still a lack of research on the use of this emergent technology in real teamwork settings. Although direct and quantitative approaches are highly desirable [2], teams interaction patterns are still poorly understood [10]. Methods for accurate group dynamics measurement are critical issues to be solved [15].

This research aims to study how team structure communication patterns can be measured and analyzed, to extend current literature over the use of sociometric badges in real settings, and to present challenges and opportunities of this promising emergent technology. Research describe how sociometric badges were used in different kind of teams, such as hackathons competitors [12], recruited specifically for study proposes [15], a crew during mission simulation [16], from first-year undergraduate engineering design course [10], from graduate students [17] or master´s students [9]. We did not find studies that describe the use of sociometric badges in a real teamwork setting.

2 Background

In order to frame the underpinnings of this case study, we briefly mention theoretical and empirical findings around communication in work teams that seeks for innovation and the use of sociometric badges as a tool to measure that complex phenomenon.

2.1 The Use of Sociometric Badges

Traditionally, sociologists have employed human observers, questionnaires or surveys to understand group dynamics for successful intervention [3, 15]. In order to minimize subjectivity [3], the unconscious bias inherent in recording group interaction data [12], remain unobtrusive [7], and responding to the need for automatic tools to measure individual and group behavior in the social sciences [18], researchers have leaned on

technology for solutions. There have been used complex measurements like videos, audios, sensors or other methods to understand and enhance group dynamics, with a high cost in data processing and delay in feedback. For addressing the complexity of team and communication dynamics wearable devices are becoming a common research tool for studying social behavior [12].

Sociometric badges are wearable sensors that may measure body movements, interactions, and speech [11]. Sociometric badges can collect unbiased and richer data than traditional methods [15]. They also reduce the large amount of post-processing data and gives researchers a chance to efficiently examine human interaction in granularity that was previously impossible [10], they allow exploring the structure of verbal interactions and provide further insight into complex team interaction process [9]. They can automatically measure individual and collective dynamics in a quantitative way and guarantee privacy due to the fact it is impossible to determine the content of the conversation or identify the speaker from the sociometric data [3].

2.2 Team Performance Communication Metrics

Within the use of this emergent technology, we identify three main verbal communication metrics related to team performance in literature, namely vocalization distribution, turn taking frequency, and overlapping speech.

First, the critical factor in a group's dynamics is the extent to which members participate in developing shared ideas [19].Vocalization distribution is the proportion of the speaking time [9]. There is enough empirical evidence to support that a balanced vocalization distribution is positively correlated with team performance [9, 10, 12, 13].There is higher team performance when less centralized communication or more sharing of ideas among multiple team members rather than a single or a few members´ communication is displayed. Dominant behavior is a key determinant in the formation of a group's social structure, and consequently group communication and dynamics. A dominant participant may have a negative effect on group's dynamics by discouraging participation of other members or imposing their thoughts on the whole group [15]. Although conversely, in practical terms, Paulus and his colleagues [19] observe that typically one or two persons dominate team conversation.

Second, turn taking frequency was defined by Kim and her colleagues [15] as each instance a participant takes over in a conversation either from another participant or from silence, so every turn taking divides a speech segment. A speech segment is any continuous stream of speech from an individual, regardless of interruption or overlap from other participants. A segment will end either by an interruption caused by another participant that resulted in the speaker to stop speaking (which means a turn taking) or by a significant length of silence.

It is not clear how turn taking frequency correlates with results. A recent study by Zhou and her colleagues [17] indicates the contradictions. On one hand, disagreement may appear as a high level of turn taking in meetings, with participants interrupting each other or frequently speaking at the same time [12]. Turn taking was found to be negatively associated with perceived collaboration quality [17]. On the other hand, studies confirm that turn taking correlates positively with the results [4, 20, 21]. The

possibility of frequent exchange is closely linked to coordination and collaboration with positive impact on team performance. Higher turn taking rates contribute to better group cohesiveness and satisfaction, generate a higher number of quality ideas and have higher performance [10]. Turn taking was significantly and positively associated with creative fluency, which provides strong support for theoretical suggestions that elaboration is a process that directly enhances group creativity [17].

Third, overlapping speech is the time that two or more members are speaking at the same time [15], is the duration of speech that speaker A and B uttered simultaneously [17]. Overlapping speech may evidence lack of hearing or disagreement, when participants cut each other off or speaking at the same time, so correlates negatively with performance [12, 17]. However, we are cautious on this metric. To Lederman [12] it was difficult to identify if overlaps mean the configuration of subgroups and regarding brief overlaps, Endedijk and her colleagues [9] clarify in their study they could not define whether this consisted of a lot of brief interruptions (e.g., a confirmatory 'yes') or fewer long interruptions (which might be experienced as more disrupting than brief confirmations) and ask for more advanced algorithms to add measures that provide more insight into overlaps effects, i.e. in relation to the length and number of interruptions.

Kim and her colleagues [14] take this emergent technology a step further and develop a Meeting Mediator (MM), a real-time portable system that shows sociometric badge outputs. Their study concludes that the use of MM has a significant effect on overlapping speaking time and interactivity level without distracting the subjects. The sociometric badges also able to detect dominant players in the group and measure their influence on other participants. Most interestingly, they highlight in groups with one or more dominant people, MM effectively reduce the dynamical difference between co-located and distributed collaboration as well as the behavioral difference between dominant and non-dominant people. The authors suggest the system encourages change in group dynamics that may lead to higher performance and satisfaction.

3 Method

This is an exploratory research, and its strategy is the elaboration of four different case studies [22]. The unit of analysis is represented by a meeting where the team joint to solve a real problem in the organization setting. First, we describe the instruments used to measure communication metrics and team performance. Second, we present the pilot test and the description implemented to collect the data. Third, we detail how we calculate metrics with the data analysis software. Finally, we describe the team's organizations as teams´ context and the characteristics of the task and meeting under study.

3.1 Instruments

In order to measure team structure communication patterns and correlate results with team performance, we use two instruments, sociometric badges during a meeting and a questionnaire, after the meeting.

The MIT Media Lab facilitates information and layouts to develop an affordable wearable technology; the Rhythm badges [12]. The badges (Fig. 1) enable to extract vocalization signals highly undersampled, which means they do not record any speech content but are capable of recording whether the user is speaking or not. They can not identify the person who is speaking. The badges are connected to a base station, and send collected information via Bluetooth. This allows measuring the communication metrics described in the analysis section.



Fig. 1. Sociometric badges.

A questionnaire with a 6-level Likert scale based on Lewis [21] performance metric is used to identify each team member´s perception about what happened throughout the meeting from a referent-shift approach [23]. The questionnaire includes the following points: (a) The team's deliverables were of excellent quality, (b) The team managed time effectively, (c) The team met important deadlines on time (d) The team did a good job at meeting [the expected or client's] needs. The questionnaire is designed to be administered individually, considering that the aggregate perspective of the participants belonging to the group is usually an accepted measure in the literature to measure the collective-team level constructs [24].

3.2 Pilot Test

The project, protocol and instruments were studied and approved by the Bioethics Committee of the Municipal Hospital of Bahía Blanca (Argentina). The protocol requires each participant to sign a formal participation consent.

A pilot test was conducted in order to evaluate badges utilization, software recording parameters, and data processing. The questionnaire was validated. The pilot test was conducted in a team of 5 engineers' members at the Universidad Nacional del Sur, which aimed to verify a series of technical issues on a project. The meeting lasted 40 minutes and allowed to measured, for example, the time it took to sign the participation consent. This pilot case allowed us to adapt the data collection instrument. We have also checked devises functioning, such as if they identify false positives from the software. Improved versions were used in the four cases under study, following the next procedure.

3.3 Procedure Description

First, the meeting was planned. Having the organization and leader authorization, we anticipated potential user's details of the technology that was going to be used and sent the consent. The meeting was schedule by the team, as their activity demanded, and researchers were informed. Second, following Lederman [12] guides, we installed the base station in the meeting room, before the meeting. Third and while each member arrived to the meeting room, we asked for the consent signature, we shifted on and helped wearing the devices. This process took 2-4 minutes, depending on how many members the meeting had.

A researcher assisted during the meetings, who has no eye contact with any participant, focused on checking the data was being collected properly by the software and registered observable interactional dynamics, such as subgroups. Forth, a form was completed with data about the exact time the badges were turn on, the formal time of the beginning and end of the meeting and every event associated with studied metrics (for example, if a member went out of the room, used the phone or a subgroup was set up). Fifth and having finished the meeting, each member handed over the badges. While each member delivered the equipment, the effect of the presence of the researcher was consulted. In all cases they expressed they had had neither distractions nor discomfort. Finally, and after the meeting, the questionnaire was sent by email to all assistants in GoogleForms format.

3.4 Data analysis

In order to process the badges data, we developed a data analysis algorithm for this special purpose, which can recognize which participants were speaking every moment. First, for each participant we extracted a subset of data where we were sure that only that participant was speaking. Second, using statistical tools we studied that subset to define rules to detect in the entire data set when each participant was likely to speak. Finally, analyzing the correlation between the audio signals of each participant, we eliminated false detections due to crosstalk. The environment noise and researcher´s notes were considered, such as a bus passing by the window (case 2) or a mobile ringing (case 4). As Lederman´s explained [12] we met metric imperfections, due is mathematically impossible to be precise with this technology. However, the devises allowed to access to team dynamics representative metrics.

In order to analyze questionnaire results, we processed responses in an Excel spreadsheet. Considering its 6 level scale, we transform each case average result into percentage.

3.5 Metric Definitions

Based on background empiric literature [9, 10, 14, 12, 17] we define metrics and indicators (shown in Table 1 with an asterisk*). Having collected and processed the data, we develop a set of indicators that serve us to complement the analysis (shown in Table 1 with a double asterisk**). Table 1 also shows indicators´ calculation and unit of measurement.

Table 1. Metric definitions and calculations details

Metric ID	Definitions	Indicator Name & Calculation	Unit of measurement
Vocalization Distribution	Fraction of time per person that distributes total speaking time during which a member speaks, regardless of interruptions or overlap speech from others	**Vocalization Distribution*:** Total member speaking time divided the meeting time	**Minutes (per member)**
Team Vocalization Distribution	Level of homogeneity or heterogeneity in which the team distributes its vocalization	**Standard Deviation ** ** considering each member vocalization distribution	**Proxy:** the lower-closest to 0, the better team balance distribution
		Dominance:** the maximum participation level divided by the average participation of the other members	**Proxy:** the higher, the more difference is between the dominant speaker and the rest of the members
		Team Vocalization Tenure:** time speech occupation over total meeting time	**% of the meeting time:** can range from 0 (no one spoke throughout the meeting) to 100% multiplied the number of members (all spoke throughout the length of the meeting)
		Clean Vocalization:** team vocalization tenure subtracting total overlap time percentage	**% of the meeting time** during which a member speaks, without counting interruptions or overlap speech from others.
Turn Taking Frequency	A turn is the number of times a member speaks after another member. A turn divides a speech segment. More turn taking frequency means shorter speech segments per member.	**Turn Taking Frequency*** is the number for each member during the entire meeting	**Count (per member)**
		Team Turn Taking:** Total turn taking divided the meeting time	**Proxy:** the higher, the faster the speed of the exchange frequency in shifts
		Average Speech Segment:** Average of speaking time per member divided turn taking count per member	**Seconds:** the higher, the longer average duration in the meeting speech segment
Overlapping Speech	Fraction of time that two or more members are speaking simultaneously.	**Overlap Time*:** Fraction of overlap speech time divided the total meeting duration	**% (per member)**
		Overlap Count:** number of participation occasions in overlapping speech	**Count (per member)**
		Total Overlap Time:** the sum of the member overlap time associated to the meeting time	**% of the meeting time:** the higher, the greater presence of overlap throughout the meeting
		Average Overlap duration:** the average of each member difference between each overlap time and overlap count	**Seconds:** the higher, the longer average duration in meeting overlap

3.6 Description of case studies

We studied four team works, belonging to different organizations. Table 2 present each team organization characteristics.

Table 2. Organizations characteristics.

N°	Sector	Years in business	Staff number
1	**Consulting Services**	10 years	Less than 10
2	**Education**	55 years	More than 500
3	**Food**	15 years	More than 100
4	**Gas Distribution**	74 years	More than 1500

Organization 1 is an association of professionals that provide management and human resources consulting services in the region, especially to small and medium size firms. Their teams set up to respond to specific client´s demands, so flexibility is a valuable competence.

Organization 2 is a public national university, funded in 1956 and represent an educational hub. It must comply with laws, resolutions and administrative decisions issued by different government agencies. It has an independent government and budget. The university is organized in departments (17) and research centers (9). There are 23,619 undergraduate students, 1,761 postgraduate students, 3,099 academic staff, 60 undergraduate careers, 64 postgraduate careers, and 581 administrative and technical staff [25]

Organization 3 has emerged as a venture entrepreneurship in 2004. In its beginnings, the firm's activity was centralized in a single point of elaboration, sales and distribution. A short time later and, as a result of the great acceptance of the product proposal, the structure has expanded: it currently has a production factory and seven distribution and sales locations. It has well established itself as a regional leading gastronomic firm; it has diversified, and currently produces more than 40 products. The organization offers a delivery service to its clients.

Organization 4 is the largest natural gas distributor in Argentina in terms of volume, covering 45% of the country in two contiguous regions. With a complex system of transportation pipelines and distribution networks that exceeds 50,000 linear kilometers in length; they supply more than 2,000,000 users in seven provinces of the country.

4 Results

Cross-boundary meetings [26] are regular in organizations as a form to address and solve problems or discuss and define future directions. Each organization planned a meeting in order to solve a current and real problem. Table 3 briefly summarizes the task for which the members were called to the meeting under study and team member characteristics.

Table 3. Team Meetings

N°	Context	Objective	Duration	Number of team members	Educational level structure Without // With grade formation
1	A client asks for a recruitment and selection service for a difficult profile to fill, the regular working plan needed to be adjusted.	Re-define steps, responsible, schedules…	50 min	3	1 // 2
2	Academic management top team seeks for an ISO certification, monitoring indicators is mandatory to achieve this organizational goal.	Analyze annual KPIs and define next period objectives	1:45 hours	7	3 // 4
3	A new online delivery service is offered in the city. The questions were: What should we do? Should we incorporate these channel sales? What impact would this have over our own delivery personnel?	Analyze pros and conts. Take decisions. Define plan to respond.	1:15 hours	6	5 // 1
4	Digital transformation is an imperative in the organization. Some sectors are using paper-based and digital systems to process customers' claims.	Analyze change difficulties, synchronize sectors and organize faster migration.	40 min	8	6 // 2

Having collected and processed data, we first analyze each case separately. We highlight that the research observations show all four meetings were flowed smoothly and harmonically and no apparent conflict was shown during them. For space reasons, we only include the full description of case 4. We also present main descriptive results of the other three cases. Then, we present a synthesis and compare results in Table 4 and discuss results as preliminary interpretations.

4.1 Cases

The eight members meeting was vocally distributed unevenly. Even though member 18 dominated the participation (2,44 dominance) the standard deviation stand at 8,12. As Fig. 2 shows, there were 3 (if not 4) members that stood out. One of them, member number 1, was the facilitator and convener of the meeting, a person that opened the meeting with the agenda items, synthesized agreements achieved during the meeting and gave a formal finishing. Also, case 2 did not show a significant dominance member. In case 1 and 3, one member dominated the vocalization participation, the leader and convener of the meeting.

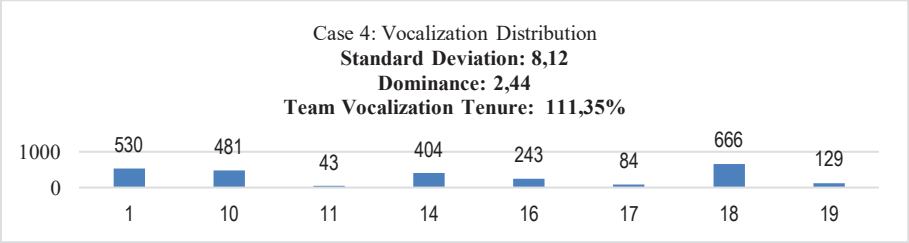

Fig. 2. Vocalization Distribution Indicators of Case 4.

Fig. 3 shows the dominance were both regarding vocalization and turn taking count –as in case 1. This feature was not present in case 2, where some members took shorter turn. The members' sum 111,35% of vocalization over the extent of the meeting, which correspond to the level of the total overlap time (36,43%). Differently, in case 1, the team vocalized among 80,7% of the meeting length, which leaves almost 20% of the meeting time to members silence.

Team turn taking speed arose up to 0,085. The slowest was case 2 (0,056) The average speech segment in case 4 was 14,10 seconds.

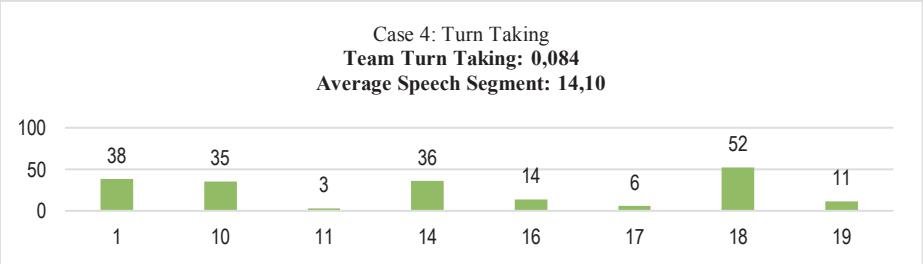

Fig. 3. Turn Taking Frequency Indicators of Case 4.

The average overlap duration of case 4 was 1,36 seconds. Besides vocalization, member 18 also contributed more than the other members to overlap count and time (see Fig. 4). The same occurred in case 1, where the member that contributed the more to overlaps was not the leader neither the facilitator. Differently, in cases 2 and 3, vocalization and overlap were balanced. In this case, the dominant member was the only that had an outstanding difference between overlap time and overlap count, meaning overlaps were longer than others´. Case 2 present this same feature among their 3 dominant members, their overlaps were also longer. Differently, in case 1 and 3 all members contributed similarly in times and duration. During case 2 meeting, the researcher observation registered one case of overlap that correspond to a member (n°5) that leaved the room in order to respond a phone call. Considering the data of the entire meeting, it seems this circumstance did not affect results significantly.

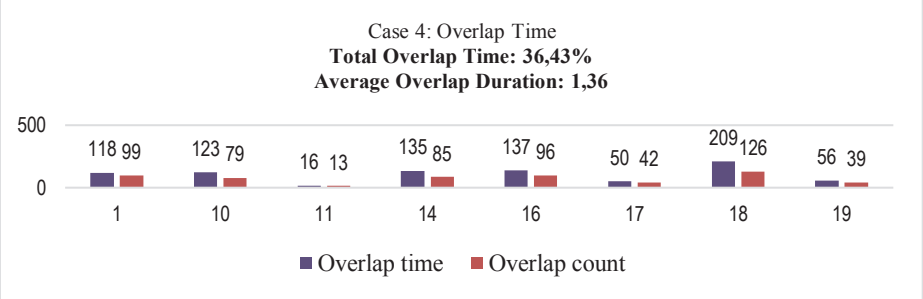

Fig. 4. Overlapping Speech Indicators of Case 4.

Thanks to observer records about case 4, we identified that in general, overlaps appeared as confirmatory interventions or short interruptions (yes, of course, in agreement, a name or reference) or as informal interactions (jokes, laughter). During the meeting, as in case 2 and 3, there were occasions when in dynamic interaction two or more members "compete" to take the turn and one managed to overcome the overlap at the cost of the other member's silence. Subsequently, the turn changed to whoever wanted to contribute. This feature mainly happened in case 3 where the flow of information run between the members quickly, team turn taking was the highest –faster turn- of the four cases (0,099).

The appearance of subgroups in short periods of time, which did not imply disruptive overlaps, was also recorded. In this case, members immediately returned, naturally and without being asked, to configure themselves as the only group. This phenomenon of subgroup assembly and natural return to the unique group was observed in this meeting of eight members, mainly. In case 3, when subgroups were sustained over time and its extent required greater concentration due to the vocalization volume increasing, the leader expressly requested to return to the single group configuration. In these situations, was registered a first functional overlapping speech moment (subgroup) and a second dysfunctional overlapping speech moment (lack of line, organization of speech and general understanding). During case 1 no subgroups were set –which in a meeting of three members would not be possible-. Still, this fact evidence case 1 overlap indicators do not correspond to subgroups.

4.2 Team Comparison and Preliminary Interpretations

Table 4 summarizes the four cases. The table includes performance indicator (members' perception about what happened throughout the meeting). According to this perception, all meetings were valued above 75%, the difference between the top (case 1) and the lowest (case 4) is 18,06%.

Table 4. Team Metric Results by Case

Metric ID	Indicator	Case 1	Case 2	Case 3	Case 4
Team Vocalization Distribution	**Standard Deviation**	15.82	7.42	7.34	8.12
	Dominance	2.95	1.63	2.38	2.44
	Team Vocalization Tenure	80.68%	108.59%	92.87%	111.35%
	Clean Vocalization	74.63%	72.84%	74.02%	74.92%
Turn Taking Frequency	**Team Turn Taking**	0.076	0.056	0.099	0.084
	Average Speech Segment (seconds)	9.68	18.73	8.99	14.10
Overlapping Speech	**Total Overlap Time**	6.05%	35.75%	18.85%	36.43%
	Average Overlap Duration (seconds)	1.10	2.00	1.29	1.36
Performance Result (scale 1-6)		5.63	5.13	4.88	4.54
		93.75%	85.25%	81.25%	75.69%

Based on the theoretical background, we understand that the lower the vocalization distribution standard deviation, the greater the homogeneity; which would indicate greater team efficiency. This indicator simplifies the comparison of the indicators related to the distribution in the vocalization [27]. Although it has been the most proven, we found it did not correlate positively in our four case studies.

The dominance indicator also contributes to this aspect of the meeting analysis, where it reflects the maximum participation level divided by the average participation of the other participants. We found no direct relationship between dominance indicator and meeting performance results neither. A series of factors could be attributed to our findings such as the size of the meeting team, if the meeting had or not a facilitator and the presence of a reference member with the technical knowledge needed to solve the meeting agenda. In addition, differently from what is indicated by the literature, we found up to 3 dominant members of the team conversation.

We found team vocalization tenure –the extent members use the meeting time to vocalize- were coherent with performance results. As long as the team vocally fits the meeting time (100% of the meeting time or less), the results hold high. To the extent the vocalization percentage exceed 100%, the perception of performance in results decreases. For example in case 4, members vocalized 111,35% and ranked last. Following this reasoning, it is interesting to connect team vocalization tenure with total overlap time percentage. We calculated clean vocalization indicator (vocalization without counting interruptions or overlap speech) This indicator itself did not display any correlation with performance results but, in our cases, where clean vocalization stood around 70-75%, performance results corresponded above 75%.

Similarly, we could not found a positive or negative direct relation in between speed frequency among members' turns nor the average speech segment duration with results. However, and considering the need to identify more clearly the explanation of overlapping speech, we could note that where the average speech segment was high (case 2 and 4) the meeting overcome the 100% of team vocalization tenure, and the total overlap time was also high. Our interpretation was that a faster turn taking could facilitate a better means of overlapping speech in team interaction.

We identified different kinds of overlapping speech, namely informal, disruptive, confirmatory, competitive for a turn and related to subgroups. Subgroups appeared when the meeting has 4 or more members. We found subgroups might have functional or dysfunctional moments; they may disappeared naturally or by demand.

In the four cases, overlapping speech metric did not correlate with performance results directly. However, we can approximate as an interpretation that when total overlap time was high but dominance was low (case 2) results were higher than when total overlap and dominance were both high (case 4). This may indicate that when vocalization was balanced, all members contributed to a synchronized and fluid conversation, meaning the interruptions and overlaps reflected this rhythm of interaction.

The average overlap duration holds below 1,36 seconds in three cases, and in case 2 it was 2 seconds. Considering the performance results and the observer notes regarding the fluidity of the meetings, this length was not disrupting in team interaction, with the exception of dysfunctional subgroups moments.

Considering team communication dynamics and thanks to the researcher observation, we offer a preliminary characterization of meeting stages. We identified a first stage, the starting one, where members arrived and located. This stage was characterized with icebreaker interaction, members exchanged informally. The interaction was not structured and dominant members appeared (for instance, the extrovert or the leader) and subgroups were dysfunctional. Disruptive and informal overlaps were observed and turn taking was faster. In a second stage, the developing stage, the group focused their activity on the convening meeting topics and defined a rhythm. Subgroups may appear and the overlapping speech was mainly disruptive, confirmatory or respond to the intention of winning a turn (competitive overlap). The speech segments were longer. Then, as the finishing stage of the meeting, the group returned to unstructured dynamics; commentaries that were not related to the convening meeting topic appeared. During this last stage, overlaps corresponded to informal interaction and turn taking got speed.

5 Conclusions and Future Research

Our study extends the understanding team structure communication patterns and provides an important contribution to research in the field of sociometric badges, being the first one that analyzed teams in real work settings. Focus on the use of the badges allowed to measure metrics that have been used previously (vocalization distribution, turn taking frequency and overlapping speech) and new indicators, built with the purpose of exploring the technological possibilities of the devices (dominance, team vocalization tenure and average speech segment, for example).

Based on previous literature, while one might argue that vocalization distribution is a good proxy for team performance, when we examined our four cases, we found that the metric should be analyzed as part of a set of indicators in context. For example, we identify subgroups and overlapping speech key mechanisms of team interactional dynamics.

We can identify at least four lines for future research using sociometric badges. First, the study of the evolution of the same team along different meetings. Second, it would be interesting to focus on technological possibilities of devises to identify and characterize more clearly different meeting stages. Third, the collection of data in a wider set of teams and organizations may allow better comparisons within cases and indicators. Fourth and finally, regarding available technology, there is great chance to incorporate artificial intelligence to give more precision to metrics.

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An Optimization Model for University Course Timetabling. A Colombian Case Study

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Abstract. Course Timetabling at universities can be defined as the scheduling of different courses in specific time slots. To carry out this process it is necessary to take into account key factors such as: available courses, the distribution of time slots and lecturers' availability. In addition, there are resources that are essential for the model performance. For instance, the available classrooms and their capacity to completely satisfy the specific demand of students. In this study, a mixed integer linear programming model is presented to find the optimal schedule of the courses. Results show that the proposed model provides feasible solutions where all the proposed factors are considered.

Keywords: University Course Timetabling, Scheduling, Mixed Integer Linear Programming, Classroom Programming

1 Introduction

Scheduling has been widely used in educational institutions due to its importance for optimizing physical and human resources [1]. Institutions such as universities, which have a high demand for subjects and students, must organize each of these resources in the best way to comply with all the quality conditions they have offer and are accountable for. Not having a systematic methodology to generate feasible schedules efficiently may result in the use of human resources to carry out the task manually. This situation worsens when considering all the different conditions given to determine the viability of schedules to be used.

For educational institutions, organizing academic schedules is not an easy task. Moreover, it is not unusual that budget for these processes is scarse, meaning that an efficient planning schedule must be carried out by qualified staff and with minimum cost. Lawrie [2] and Tripathy [3] took that into consideration and defined the number of hours per week that were necessary for a course to prevent courses from overlapping, as main requirements. These generates the fulfillment of the estimated hours and the assignment of teachers without conflict. During the following years, different authors adapted these first models, adding specific

conditions for their institutions or some other general ones that could be applied to other studies. An example of this is the study by Schimmelpfeng [4], where the application of a Mixed Integer Programming (MIP) model was carried out at the German School of Economics and Administration, adding elements such as the capacity of the available rooms and establishing as a objective function the minimization of violation of planning constraints.

The aim of this paper is to propose a MIP model for the course timetabling in a Colombian University. In this case study, an academic program and its core courses are considered. The academic program consists in 10-semesters, 17 core subjects, each with a certain number of subgroups determined by the expected demand of students. The model focuses mainly on avoiding the overlapping of subjects from the same semester, guaranteeing that students can enroll the courses of the semester they are. The proposed MIP model also considers the classroom capacity, the assignment of professors to courses according to a subject ability and the type of contract to determine the maximum number of hours each professor can teach per week.

The rest of this paper is organized as follows. Section 2 presents a bibliometric analysis of related studies. Section 3 shows the MIP model formulation. Section 4 presents the computational results. Lastly, Section 5 drawns some conclusions of the study and provides some interesting avenues for future research.

2 Bibliometric Analysis

In order to delve deeper into schedule and timetabling problems, a bibliometric analysis was carried out. Bibliometric analysis helps one to understand who are the authors more interested on a specific topic, as well as which are the journals, countries and institutions that have worked more on it. (Sierra-Henao et al., 2019) [5]. In addition, citation and co- citation analysis help identify the most cited authors, articles and prevailing topics. According to Noyons et al. (1999) [6], bibliometrics combine two main procedures: scientific mapping and performance analysis. The importance of this type of analysis is to estimate how well the reviewed topics have been studied and draw conclusions from there, as mentioned by Solano, Castellanos, Rodríguez and Hernández [7].

Table 1 shows a summary of the methodology followed for the analysis. The bibliometric analysis was based on the literature collected from Scopus database (www.scopus.com) as it is defined as "the largest abstract and citation database, with over 1.4 billion cited references indexed from high-quality of peer-reviewed literature as scientific journals, books and conference proceedings" (Elsevier, 2020) [8].

Unit of analysis	Published
Period of analysis	2010 to 2020
Search engine	Scopus
Query string	TITLE-ABS-KEY((course OR class*) AND timetable AND schedul* AND optim*) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SUBJAREA , "COMP") OR LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "MATH") OR LIMIT-TO (SUBJAREA , "DECI"))
Number of evaluated articles	1,059

Table 1. Research method.

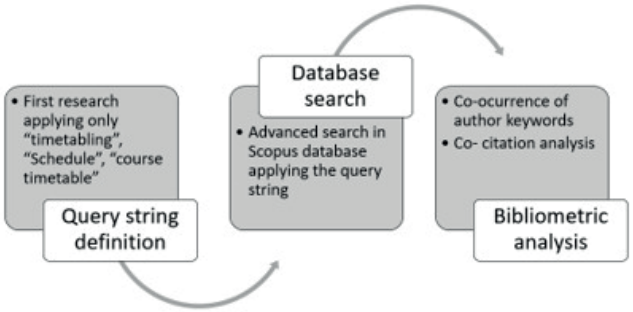

Figure 2. Summary of methodology used.

After having collected the search results from the query string, a software called VOSviewer was used. This software is a tool for building and visualizing bibliometric networks for better understanding and detect non relevant repeating terms to excluded them from the list. VOSviewer was developed by Van Eck and Waltman [9] where the software has the capacity to distinguish two types of bibliographic maps, one of them related between the investigated elements and the other facilitates the identification of groups of related elements.

First of all, an analysis of author keywords was performed. Figure 2 shows the 85 most frequent keywords with at least three occurrences for easier reading. Keywords are represented with circles, where the largest circles represent the keywords that have been used the most. As shown in figure 2, eight different clusters are separated by distinct colors. The green cluster identified as "timetabling", represents the prescriptive approaches for solving this type of problems.

Keywords related with "scheduling problem", such as "combinatorial optimization" and "course timetabling problem" appear in the yellow cluster. Other words such as "timetabling problem", "genetic algorithm", "high school timetabling problem", "exam timetabling" and "particle swarm optimization" appear in the purple, blue, orange, red and light blue clusters, respectively. In addition, the brown subgroup are linked with "robustness" and "course timetabling" topics.

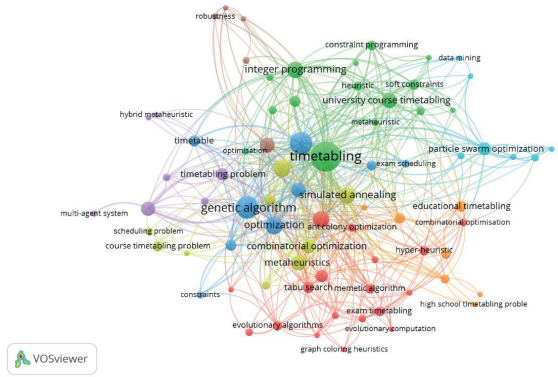

Figure 2. Co-occurrence of author keywords.

Additionally, in order to obtain a deeper insight into the gained results, figure 3 shows the timeline visualization overlay of the co-occurrence of author keywords on the evaluated contributors. In other words, it exhibits the evolution of the different keywords through the years. Considering what was mentioned above, new or trending concepts can be highlighted: university course timetabling, educational timetabling, bi-criteria optimization, , and integer linear programming. The latter has the highest average publication year among 85 keywords between 2018. At the other end of the spectrum, keywords as “course timetabling problem” and “school timetabling problem” have been less popular recently with an average publication year between 2012.

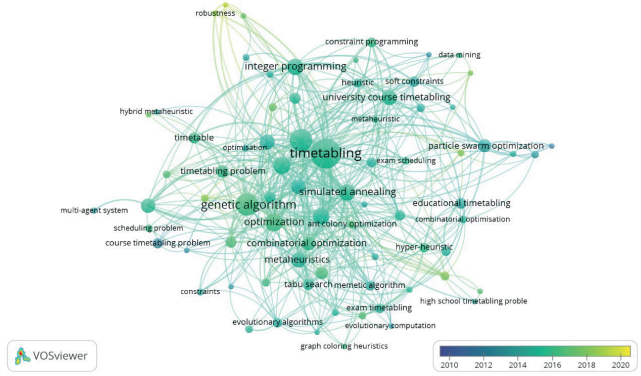

Figure 3. Evolution of co-occurrence of author keywords from 2010 to 2020.

For the co-citation of authors analysis, a minimum of 20 citations per author was considered. Out of the 8,702 authors within the analysis, 218 of them met the threshold. As shown in figure 4, authors were classified in 5 different clusters evaluating the strength of correlations between co-citations. Authors Burke, E.K, Mccollum, B. and Qu, R, are the most relevant and most cited for timetabling and scheduling related topics. Table 2 shows a summary on the top 10 most cited

authors, their total citations and the references to which citations are associated.

Rank	Authors	Year	Title	TC
1	Burke and Bykov[10]	2016	An adaptive flex-deluge approach to university exam timetabling	1,204
2	Abdul Rahman et al.[11]	2014	Adaptive linear combination of heuristic ordering in constructing examination timetables	735
3	Qu et al.[12]	2015	Hybridising heuristics within an estimation distribution algorithm for examination timetabling	491
4	Abdullah and Turabieh[13]	2012	On the use of multi neighbourhood structures within a Tabubased memetic approach to university timetabling problems	433
5	Burke et al. [14]	2010	Hybrid variable neighbourhood approaches to university exam timetabling	391
6	McCollum et al.[15]	2010	Setting the research agenda in automated timetabling: The second international timetabling competition	373
7	Abuhamdah et al. [16]	2014	Population based Local Search for university course timetabling problems	315
8	Lewis and Thompson [17]	2015	Analysing the effects of solution space connectivity with an effective metaheuristic for the course timetabling problem	218
9	Muklason et al.[18]	2017	Fairness in examination timetabling: Student preferences and extended formulations	217
10	Oner et al.[19]	2011	Optimization of university course scheduling problem with a hybrid artificial bee colony algorithm	192

Table 2. Top 10 most cited Authors

3 Problem Formulation

This section presents a MIP model to schedule a specific number of subjects, considering institutional policies and physical resources characteristics. The objective function and operational constraints aim to minimize the number of missed hours to fulfill professors workload while assuring that all classes are programmed and avoiding the overlapping of subjects from the same semester.

Therefore, the model considers students demand, professor availability, classrooms capacity, days and hours where classes could be programmed, and type of contract (full or part time) of the professors, seeking to generate optimal schedules for both students and professors. The following sections present the sets, parameters, decision variables, objective function and operational constraints of the model.

3.1 Indices

The following indices were defined for the proper development of the model:

i = timeslots (T1: 7-9, T2: 9-11, T3: 11-13, T4: 13-15, T5: 15-17, T6: 17-19, T7: 8-10, T8: 10-12, T9: 12-14, T10: 14-16, T11: 16-18, T12: 7-10, T13: 10-13, T14: 13-16, T15: 16-19, T16: 8-11, T17: 11-14, T18: 14-17, T19: 9-12, T20: 12-15, T21: 15-18). These are defined considering that courses may be offered in two- and three-hours spaces only.
j = days (Monday,..., Friday).
k = courses (C1,..., C59).
p = professors (1,...,25).
t = contract type (full time, part time).
s = semester (1,..., 10).
a = available classrooms (S1,..., S10).
m = number of days in which the class is taught. That is, a class needs either one day a week or two.

3.2 Parameters

The following parameters were defined for the development of the model:

$Hours_k$= Week hours for course k.
$Maxdays_m$= Days m per week required for course. Either one or two.
$Numberhours_i$= Hours for timeslot i.
$Capacity_a$= Student capacity of classroom a.
$Students_k$ = Expected demand of students for course k.
$Contract_{p,t}$= 0-1 Matrix indicating if professor p has contract type t.
$Semester_{k,s}$= 0-1 Matrix indicating if course k is offered in semester s.
$Timeslots_{i,i'}$= 0-1 Matrix indicating if timeslot i does not overlap with timeslot i'.
$Courseprof_{k,p}$= 0-1 Matrix indicating if course k can be taught by professor p.
$Courseday_{k,m}$= 0-1 Matrix indicating if course p requires m days per week.
$Disp_{p,k,i,j}$= 0-1 Matrix indicating if professor p is available for teaching course k during timeslot i on day j.
$Minhoursparttime$= Maximum number of teaching hours per week for part-time lecturers.
$Maxhoursfulltime$= Minimum number of teaching hours per week for full-time professors.
$Maxhoursfulltime$= Maximum number of teaching hours that can be allocated per day for each semester.
$BigM$= Very large integer value.

3.3 Decision Variables

The following decision variables were defined for the model:

$X_{p,k,i,j}$= 1 if professor p teaches course k in timeslot i of day j, 0 otherwise.
$Y_{k,i,j}$= 1 if course k is taught in timeslot i of day j, 0 otherwise.
$N_{a,i,k,j}$= 1 if course k is taught in timeslot i of day j in classroom a, 0 otherwise.
$W_{p.k}$= If professor p teaches course k.
$G_{k,j}$= If course k is taught on day j.
$DELTA_p$= Hours professor p misses to fulfill his workload.
$DELTA2_{p,k,i,j}$= Hours missed to assign all courses.

3.4 Objective Function

The model is aimed at minimizing the hours professor p misses to fulfill his workload:

$$min\ Z = BigM \cdot \sum_{p} DELTA_p \tag{1}$$

3.5 Constraints

The following constraints were considered for the problem:

$$\sum_i \sum_j Y_{k,i,j} \cdot Numberhours_i = Hours_k, \ \forall k \tag{2}$$

$$\sum_i Y_{k,i,j} \leq 1, \ \forall k, j | Courseday_{k,m} = 2 \tag{3}$$

$$G_{k,j} + G_{k,j+1} \leq 1, \ \forall k, j | j \neq Friday \tag{4}$$

$$\sum_j G_{k,j} \cdot Courseday_{k,m} \leq Maxdays_m, \ \forall k, m \tag{5}$$

$$\sum_k Y_{k,i,j} \cdot Semester_{k,s} \leq 1, \ \forall i, j, s \tag{6}$$

$$Y_{k,i,j} = 0, \ \forall k, i = \{T4, T5, T6, T10, T11, T14, T15, T18, T20, T21\}, j = Friday \tag{7}$$

$$\sum_k \sum_i Y_{k,i,j} \cdot Semester_{k,s} \leq Maxhoursday, \ \forall k, s \tag{8}$$

$$\sum_p W_{p,k} \leq 1, \ \forall k \tag{9}$$

$$\sum_p X_{p,k,i,j} \leq 1, \ \forall k, i, j \tag{10}$$

$$\sum_k X_{p,k,i,j} + \sum_k \sum_{i' | i' \neq i \wedge Timeslots_{i,i'} = 0} X_{p,k,i',j} \leq 1, \ \forall p, i, j \tag{11}$$

$$X_{p,k,i,j} \leq Courseprof_{p,k}, \ \forall p, k, i, j \tag{12}$$

$$\sum_k \sum_i \sum_j X_{p,k,i,j} \cdot Contract_{p,t} \geq Minhoursfulltime - DELTA_p, \ \forall p, t = Fulltime \tag{13}$$

$$\sum_k \sum_i \sum_j X_{p,k,i,j} \cdot Contract_{p,t} \leq Maxhoursparttime, \ \forall p, t = PartTime \tag{14}$$

$$\sum_p X_{p,k,i,j} = Y_{k,i,j} \ \forall k, i, j \tag{15}$$

$$X_{p,k,i,j} \leq disp_{p,i,j} + DELTA2_{p,k,i,j},\ \forall p,k,i,j \tag{16}$$

$$\sum_{a} N_{a,i,k,j} \leq 1,\ \forall i,k,j \tag{17}$$

$$\sum_{k} N_{a,i,k,j} + \sum_{k} \sum_{i'|i' \neq i \wedge Timeslots_{i,i'}=0} N_{a,i',k,j} \leq 1,\ \forall i,j,a \tag{18}$$

$$\sum_{k} N_{a,i,k,j} \cdot Students_k \leq Capacity_a,\ \forall a,i,j \tag{19}$$

$$\sum_{k} N_{a,i,k,j} = Y_{k,i,j},\ \forall i,j,k \tag{20}$$

$$DELTA2_{p,k,i,j} \leq 1,\ \forall p,k,i,j \tag{21}$$

$$W_{p,k} \leq 1,\ \forall p,k \tag{22}$$

$$G_{k,i} \leq 1,\ \forall k,j \tag{23}$$

$$X_{p,k,i,j} \leq W_{p,k},\ \forall p,k,i,j \tag{24}$$

$$Y_{k,i,j} \leq G_{k,j}\ \forall k,i,j \tag{25}$$

$$X_{p,k,i,j}, Y_{k,i,j}, N_{a,i,k,j} \in (0,1), \forall i,j,k,p,a \tag{26}$$

$$W_{p,k}, G_{k,j}, DELTA_p, DELTA2_{p,k,i,j} \geq 0, \forall j,k,p \tag{27}$$

Constraints 2 guarantee that all the hours of each class are scheduled. Constraints 3 guarantee that, if a course has more than one session per week (i.e., requires two or more days of the week), the sessions of the class cannot be scheduled on the same day. Constraints 4 apply to those subjects that require days between their sections, in this case at least one day in between. Constraints 5 guarantee that a class cannot be programmed in more days than it is permitted to. In addition, it is necessary to ensure that classes that belong to the same semester do not overlap, this is done by constraints 6. Considering the university, Friday afternoons are reserved for postgraduate courses, meaning that constraints 7 guarantee that no undergraduate classes are assigned during said timeslots. Constraints 8 limit the maximum number of hours a day that can be taught to each semester.

It is also considered that each of the courses may be taught by a single professor, just as they may teach only one class at a time. This is ensured with constraints 9, 10 and 11. Constraints 12 establish that professors will only be able to teach courses that they are able to teach. Additionally, according to the contract type, full-time professors must teach a minimum 6 hours of class per week, while part-time professors may dictate maximum 21 hours. This is done in constraints 13 and 14 respectively. Constraints 15 establish that professors can only be assigned to courses-slots that have already been assigned. Part-time professors have a certain availability according to their needs. Constraints 16 contemplate the availability matrix of all professors, both full-time and part-time professor, in order to assign them to courses that are available in time slots to teach the class.

For the last resource (i.e., classrooms), constraints 17 ensure that each class may be assigned to only one timeslot on a single day. On the other hand, constraints 18 guarantee that classrooms may have only one course allocated on each timeslot. Constraints 19 establish that all courses will be assigned to classroom that can support the expected student demand. Lastly, the number of classrooms assigned must correspond to the number of courses in each of the time slots of each day. This is given by constraints 20. Constraints 21 to 25 establish relationship conditions between variables, and constraints 24 and 25 indicate the nature of the variables of the model.

4 Results

The proposed model was coded and solved using GAMS (General Algebraic Modeling System) version 28.2.0 and solved using CPLEX on a laptop computer equiped with an Intel Core i5 processor, 8GB RAM and a 64-bit Windows 10 operating system.

For this particular project, it is important to consider, within the result analysis, different scenarios that provide useful information for decision makers. Despite the foundations of the model being exclusively on course timetabling, it is ideal to develop ideas that revolve on the impact that the model may have on other areas, such as economics or the optimization of resource utilization.

The structure of the scenarios considered is based on two variables: teachers' availability and courses' demand. Based on information shared by the University, the code states an initial expected students demand for each course and a specific amount of groups for dividing students in order to meet classrooms maximum capacity and a homogeneous distribution. For the problem analyzed in this paper, only ten classrooms of the university were considered, seven of them can accommodate 40 people while the other three have a capacity for 30. The academic program has 20 teachers, 12 of them are part-time, while the rest

are full-time teachers.

For evaluating different scenarios, eight indicators were selected, depending on classrooms, courses, teachers and time frames. The following indicators were defined: classroom usage hours per day (%HU), classroom average occupied capacity (%AVG CAP), scheduled and unscheduled courses (%CA and %UC, respectively), assigned full- and part-time professors, critical time slots, and number of classrooms used.

Three scenarios were examined. The first one with the normal expected student demand. The second one consideres a 10% demand increase. It is worth mentioning, that in this scenario classes still have a maximum number of 40 students, as this is the largest classroom capacity. The third one evaluates a 10% demand decrease. In addition, each scenario considers five possible professor availability (100%, 75%, 60%, 50% and 40%)

		100%	**75%**	**60%**	**50%**	**40%**
Classrooms	%HU	33.82%	33.82%	33.82%	33.27%	32.73%
	%AVG CAP	91.66%	90.06%	83.55%	88.98%	91.70%
Courses	%CA	100%	100%	100%	98%	97%
	%UC	0%	0%	0%	2%	3%
Professors Used	Full-Time	8	8	8	8	8
	Lecturers	10	12	11	12	12
Critical Hour		17-18	8-9	9-10	8-9	9-10
Classrooms Used		10	10	9	10	10
Used Resources Indicators		**100%**	**75%**	**60%**	**50%**	**40%**
Classrooms	%HU	33.82%	33.82%	37.58%	33.27%	32.73%
	%AVG CAP	91.66%	90.06%	92.84%	88.98%	91.70%

Table 3. Results with a students demand decrease of 10%.

This first scenario, represented in Table 3, is based on the usual expected demand for each course. It is very important to highlight the fact that with the 40% and 50% professors' availability the total courses were not assigned. Despite the latter, the percentage of average capacity used for the 40% scenario, is the best within this frame, mainly because of the use of classrooms 7 and 10, whose capacities were entirely used by one course in a time frame, this is why these spaces have the lowest percentage of hours used. It is important to point out that the teacher 19 is the only entitled to teach for 6 groups due to its subject speciality; therefore when the availability is less than 60%, the professor is not able to teach all of them, in the 40% he matches 4 out of 6 and 5 out of 6 in the

scenario with 50% of professor availability.

Once it is possible to teach all the courses due to professors' availability, an interesting phenomenon appears: the proposed schedule distributed the hours through the classrooms in a very similar way, resulting in an equal percentage of used hours. Nevertheless, it is interesting to see that the average capacity used increases as the availability does, stating the fact that when teachers have better availability, it is more likely to use resources better.

However, in the scenario with 60% of professor availability, there is a fact that needs to be taken into account: not all the classrooms are used, that is, there is at least one empty classroom which increases the usage percentage of the classrooms. That is the reason why the second part of Table 3 is important, because it takes into account only used resources. Therefore, analyzing the behavior of the results, the 60% scenario is the best possible, regarding average capacity used of the classrooms and the hours used. This is explained by the fact that, the model focuses mainly on avoiding the overlapping of subjects from the same semester and ensuring certain amount of hours for part-time professors.

Students demand increases 10%		**100%**	**75%**	**60%**	**50%**	**40%**
Classrooms	%HU	33.82%	33.27%	33.82%	33.09%	33.09%
	%AVG CAP	74.89%	82.40%	82.22%	80.46%	80.35%
Courses	%CA	100%	100%	100%	98%	97%
	%UC	0%	0%	0%	2%	3%
Professors Used	Full-Time	8	8	8	8	8
	Lecturers	9	10	10	11	11
Critical Hour		17 - 18	8 - 9	8 - 9	9 - 10	8 - 9
Classrooms Used		8	9	9	9	9
Used Resources Indicators		**100%**	**75%**	**60%**	**50%**	**40%**
Classrooms	%HU	42.27%	36.97%	37.58%	36.77%	36.77%
	%AVG CAP	93.61%	91.55%	91.35%	89.40%	89.27%

Table 4. Results with a students demand decrease of 10%.

The results for the second scenario are presented in Table 4. It can be observed that the best used hours percentage is achieved with a 100% professor availability. Basically, when demand increased there were only 2 courses that could be taught in less than 30 people capacity classrooms, each of them with 22 students demand. The model scheduled these two classes in one classroom, leaving low demands concentrated in one space and not distributed, saving the possibility of lowering the average of the rooms with a capacity of 40 people. This scenario is the best possible for all indicators: hours used, average classroom capacity, classrooms used and teachers scheduled. Nevertheless, all the instances

(i.e., 75%, 60%, 50% and 40%) for this scenario have a good performance in terms of average capacity used.

Students demand decreases 10%		**100%**	**75%**	**60%**	**50%**	**40%**
Classrooms	**%HU**	33.82%	33.82%	34.18%	33.27%	32.73%
	%AVG CAP	84.04%	84.34%	81.99%	83.96%	81.89%
Courses	**%CA**	100%	100%	100%	98%	97%
	%UC	0%	0%	0%	2%	3%
Professors Used	**Full-Time**	8	8	8	8	8
	Lecturers	10	12	11	12	12
Critical Hour		9-10	12-13	17-18	11-12	12-13
Classrooms Used		10	10	10	10	10

Table 5. Results with a students demand decrease of 10%.

For the last scenario, when demand decreases, the model tends to distribute equally the classes within the classrooms as it can be concluded after analysing Table 5. For the different variants of teachers' availability, the 10 classrooms were used; all of them with less than 85% capacity used. This is due to the use of all classrooms where the low and high students courses are mixed and the fact the demand itself decreased. It is really interesting the fact that when demand is lower the model tends to distribute almost equally teachers and classrooms. This could be explained by considering that a demand decrease would generate smaller groups and, therefore, a better usage could be achieved for the classrooms with capacity for 30 students.

5 Conclusions and Future Research

This paper studied a university course timetabling problem. The objective was to schedule the set of courses of an academic program while professors and classrooms were assigned. A set of data from a Colombian University was taken as a sample to carry out a mathematical model that meets the conditions of schedules, crossings of subjects from the same semester, the maximum number of hours that a professor can dictate and keeping in mind the demand of students for each of the courses to allocate classrooms.

The problem is solved and provides to the researchers a tool to assess and evaluate different scenarios. The computational results show that it is possible adapt the model to different educational scenarios that require the optimal use of resources. The initial conditions are very favourable for the University as classrooms and teachers are enough. Nevertheless, numbers may highlight the underuse of available classrooms and the possibility of leaving these spaces for

another purpose; for all scenarios at least 57% hours are free in the classrooms, meaning that other programs could take advantage of this spaces.

The results also show that the model can comply with the guidelines established by the board of directors and the quality standards necessary in the academic offer. This is clear as the scheduling conditions can be modified to meet specific requirements and make the assignment process more complete, while maintaining high levels of service for both students and teachers and for the institution.

As future research, the model can be considered to be applied with all academic programs of the university to coordinate efficiently the manage of resources and to deliver one system that take control of them. Also, the inclusion of distances between classrooms can be contemplated as part of a new optimization criterion. The route that students and teachers must take could be an objective to take into account when there are two or more consecutive classes, so the less distance they travel the more time they will have to arrive. Also, integrating other scenarios with alternate students demand. In addition, as in the result analysis, assigning an opening cost for each classroom and each time frame, could transform the programming into an optimization tool as well.

It is also possible to add preference conditions at specific times, determined by the institutions to give priority to other academic activities. This should contain a matrix with weights for each of the time slots where it will be possible to indicate which of them are more pertinent to specific interests. Finally, new ways of addressing the problem can be designed, such as heuristic methods, that allow finding feasible solutions comparable with the results obtained in this research and obtaining conclusions about the performance of the models and the management of resources for their optimization.

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Identificação de fatores para avaliação da qualidade de energia elétrica: os impactos na geração, distribuição e setores de consumo

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Resumo. A qualidade da energia elétrica é importante para todos os setores da cadeia de fornecimento, desde a geração até a transmissão e distribuição da eletricidade. O aumento do número de empresas resulta em um acréscimo de cargas na rede, tornando necessário um monitoramento adequado da qualidade de energia, tanto pelas distribuidoras quanto pelos consumidores. A baixa qualidade de energia elétrica independente da sua causa, pode gerar perdas significativas aos consumidores, sendo as indústrias as mais afetadas em razão do seu alto consumo para produção de bens. Os distúrbios e as perdas de energia podem ocasionar a queima ou mau funcionamento de equipamentos, afetando diretamente o processo produtivo. É necessário identificar através do monitoramento, medição e análise, as situações que afetam a qualidade da energia em todos os segmentos. Nessa perspectiva, o presente estudo tem como objetivo realizar uma revisão sistemática de literatura para identificar os fatores que mais influenciam na qualidade do fornecimento da energia elétrica. O conhecimento dos fatores torna possível às organizações traçar um plano de gerenciamento da qualidade, podendo gerar um maior investimento em tecnologias para melhoria da produção e diminuição de gastos advindos desse consumo.

Palavras-chave: Qualidade da Energia Elétrica, Revisão Sistemática, Fatores, Fornecimento de Energia, Setor Elétrico Brasileiro.

1 Introdução

Nos setores industriais, a energia elétrica é considerada um dos produtos mais caros necessários à produção de bens [1], sendo gastos aproximadamente um terço da energia disponível [2], o que leva as empresas a equacionarem seus gastos advindos desse consumo [3]. A Energy Information Administration (EIA) estima que até 2050 a nível mundial, haja um aumento de aproximadamente 50% no uso da energia [4], sendo a China responsável por um quarto do consumo mundial de eletricidade [5]. No Brasil, embora o setor residencial seja responsável por 86,1% das unidades consumidoras de energia elétrica, em relação ao consumo, fica atrás do setor industrial, sendo

consumidos 137.615 GWh e 169.625 GWh de energia respectivamente [6].Um fator que pode condicionar às empresas perdas financeiras significativas é a qualidade da energia [7], sendo seu fraco desempenho prejudicial a todos segmentos da organização. Seu impacto está associado a questões como perda de produção, falhas de equipamentos, custos adicionais de operação e investimentos [8].

Externas às organizações, as distribuidoras de energia elétrica são responsáveis pelo fornecimento confiável e de qualidade da energia elétrica às empresas. Como esse fornecimento em muitos países é um monopólio natural, os clientes insatisfeitos com a qualidade ou com os preços pagos, acabam sem alternativas de troca de fornecedor. Isso aumenta a importância do monitoramento do desempenho das concessionárias de energia por parte dos órgãos reguladores [9]. Embora cada país possua seus próprios padrões de qualidade da energia, há diretrizes internacionais, como a norma técnica EN 50160 aplicada na Europa e aceita por todos os países, garantindo uma maior compatibilidade de padrões [10]. No Brasil, criada pela Lei n° 9.427, a Agência Nacional de Energia Elétrica (ANEEL) é a organização responsável por regular e fiscalizar o mercado de energia, monitorando também sua qualidade até os consumidores.

A avaliação da qualidade da energia elétrica é uma área que abrange toda cadeia de fornecimento, sendo importante desde a geração até a transmissão e distribuição da eletricidade [7]. No entanto, deve-se considerar também, que o aumento do número de empresas resulta em um acréscimo de cargas na rede, o que torna necessário um monitoramento adequado da qualidade de energia tanto pelas distribuidoras quanto pelos consumidores [8]. Oprea e Andrei [10] destacam ainda que as empresas ao investirem no desenvolvimento de tecnologias e equipamentos, acabam perturbando a linearidade da rede, afetando diretamente na qualidade da energia.

Os autores Dang e La [9] apontam em seu estudo, que a confiabilidade da rede elétrica aumenta a probabilidade de investimentos no setor agrícola, além do número de dias úteis a serem utilizados. Os autores destacam ainda que uma melhoria de 1% na qualidade da rede elétrica aumenta em 3,6% a probabilidade de se investir nesse setor. Já os autores Rusinaru et al. [8] discutiram em suas pesquisas uma nova abordagem para avaliar a qualidade da energia nas redes de distribuição. Para isso, um relatório de informações foi discutido, onde os fenômenos relacionados a qualidade de energia são avaliados e exibidos de maneira unitária, possibilitando a criação de mapas de perturbações e simplificando informações para que as empresas de distribuição compreendam facilmente o estado da qualidade da energia em sua rede. Gheorghe et al. [11] destacam que o funcionamento do sistema de monitoramento da qualidade de energia deve integrar aspectos técnicos, regulatórios e gerenciais para todos os participantes do mercado de energia. Sendo os aspectos técnicos a identificação de perturbações que causam a degradação da energia. Regulatórios consiste em uma estrutura para o monitoramento e medição, estabelecendo padrões e indicadores que caracterizem a qualidade para cada perturbação. E os aspectos gerenciais são as estratégias ou políticas para se monitorar os indicadores de qualidade, garantindo os padrões impostos na regulamentação. Os autores ainda colocam que uma gestão da qualidade de energia compreende sete etapas principais, estas apresentadas na Fig. 1.

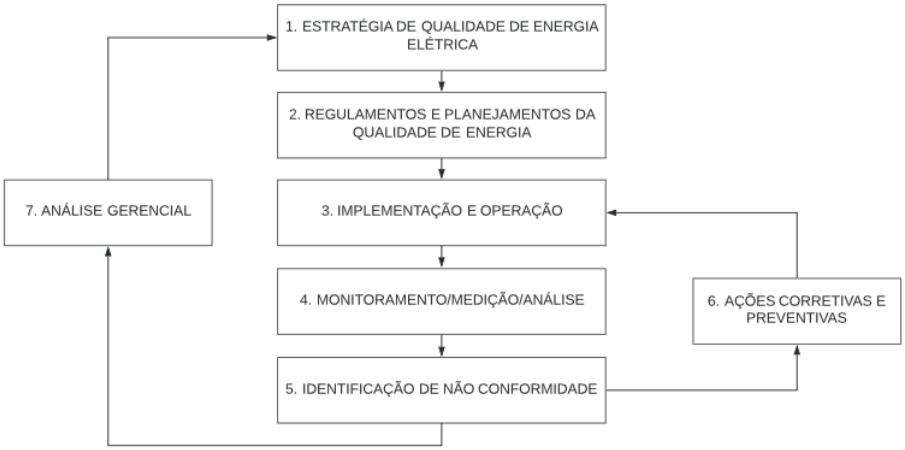

Fig. 1. Sete etapas da gestão da qualidade (Fonte: Gheorghe et al. [11])

É importante, porém, que os consumidores saibam identificar através do monitoramento, medição e análise, as situações que afetam a qualidade da energia em seus estabelecimentos. Com estratégias bem definidas, ter em vista não só os aspectos dependentes dos serviços das distribuidoras, mas também, aqueles relacionados ao meio ambiente e os vinculados aos seus processos, como equipamentos e tecnologias. Nesse sentido, o presente estudo tem como objetivo realizar uma revisão sistemática de literatura para identificar os fatores que mais influenciam na qualidade do fornecimento da energia elétrica utilizada, principal insumo dos processos industriais. Com essa abordagem, será possível a busca por soluções para mitigar tais impactos, proporcionando a redução de prejuízos advindos do consumo de energia elétrica aos consumidores, como a economia na fatura de energia elétrica e o aumento da produtividade das empresas.

2 Qualidade da Energia Elétrica

Neste capítulo serão apresentados conceitos fundamentais para contextualização e condução do estudo. O primeiro tópico apresenta os aspectos sobre os fenômenos que afetam a qualidade da energia elétrica e as percepções do mercado. Na sequência, o segundo tópico traz uma discussão sobre a sustentabilidade e o monitoramento da energia elétrica, abordando tecnologias e requisitos que permitem ao consumidor um melhor controle da qualidade da energia que recebem.

2.1 Fenômenos que afetam a qualidade de energia e as percepções do mercado

O fornecimento de energia elétrica confiável está relacionado com as questões de frequência das interrupções de energia. Assim, informações associadas as condições operacionais de equipamentos desempenham papel relevante no comportamento dos sistemas elétricos [12]. Uma vez que, existem eventos no sistema de energia que são associados ao baixo nível de qualidade de energia, como as oscilações, queda de tensão, cargas de desequilíbrio, distorção harmônica e menor fator de potência. Ao analisar historicamente os impactos de qualidade de energia mais prejudiciais para sociedade, conclui-se que estes são decorrentes de interrupções de longa duração, o que resulta em custo elevado. E, a substituição de equipamentos ineficientes juntamente com a análise das atividades de desperdícios contribuem com um aumento significativo na qualidade de energia [13,14].

Um estudo realizado por Pawawoi et al. [15] verificou o efeito de melhoria da qualidade para perda de energia nas linhas de distribuição de edifícios durante uma semana. Foi possível constatar que quando o consumo de eletricidade é relativamente pequeno, existe uma redução da perda de energia. Verificou-se que a redução de perdas de energia na linha de distribuição de cada edifício é proporcional ao nível de qualidade de energia da carga. Logo, o estudo apresenta que uma baixa qualidade da energia pode causar interferência no seu fornecimento.

Segundo Falchetta, Kasamba e Parkinson [16] na África subsaariana, a dependência da energia hidrelétrica representa um aspecto crítico para o desenvolvimento sustentável. Assim como na África muitas regiões carecem de meios acessíveis diante de perturbações temporárias causadas por fatores hidro climáticos como períodos prolongados de secas. As consequências desse fato são as quedas de energia e apagões recorrentes que implicam em questões comerciais, residenciais e perda de competitividade durante as anomalias de precipitação [17]. Ainda, observa-se que a interrupção de fornecimento aos consumidores ocasiona impactos diretos na produção econômica, através da perda de produção, matéria prima e horas trabalhadas, assim como também impactos indiretos, como perda de lazer e segurança [18].

Em relação as percepções do mercado, sabe-se que a energia elétrica apresenta o seu valor por MWh vendido ou consumido [18]. Onde, as variações na qualidade de energia que é fornecida podem acarretar em prejuízos para a sociedade, devido as alterações no seu fornecimento. Segundo a ANEEL [20], a distribuição de energia elétrica deve atender a dois conceitos de qualidade básicos como a qualidade de serviço prestados que compreende a avaliação de interrupções no fornecimento de energia elétrica e a qualidade do produto, que está relacionada à conformidade de tensão em regime permanente e as perturbações na forma de onda de tensão.

Assim, é possível entender que cada agente do setor elétrico apresenta uma percepção em relação ao custo de qualidade [21]. De maneira geral a distribuidora percebe apenas nas suas receitas e custos relativos a venda de energia com os investimentos na rede, somados ao custo de operação e manutenção desta. Uma perda decorrente da queda de consumo implica em custo para distribuidoras, que não ganham pela venda de energia, mas a receita esperada é baseada no consumo previsto. Já os

consumidores apresentam atividades afetadas pela energia elétrica, como preço de compra e prejuízos pela falta de energia como por exemplo uma parada total do processo produtivo. Por fim, o agente regulador é aquele que equilibra o mercado com regras e proporciona resultados para a sociedade [18].

2.2 Sustentabilidade de monitoramento da energia elétrica

Segundo Ferreira [23] a baixa qualidade de energia elétrica, independente da sua causa, pode gerar perdas significativas aos consumidores de energia, sendo as indústrias as mais afetadas, devido aos distúrbios que podem ocasionar um mau funcionamento e até mesmo queima de equipamentos. Esse cenário desperta preocupação por parte de concessionárias de energia elétrica em garantir a qualidade do produto. Conforme ANEEL [24], a qualidade percebida pelo consumidor de uma concessionária ou permissionária de serviço público de distribuição de energia elétrica é avaliada de acordo com o Módulo 8 do PRODIST, documento que fornece os procedimentos referentes à qualidade da energia elétrica, onde aborda a qualidade do produto e a qualidade do serviço prestado, enquanto que as Condições Gerais de Fornecimento, presente na Resolução Normativa nº 414/2010, apresentam os aspectos relacionados à qualidade do atendimento ao consumidor, do atendimento comercial, atendimento telefônico e tratamento das informações.

Ao mesmo tempo que este cenário desperta preocupação por parte de concessionárias, estimula também o interesse dos usuários de energia em monitorar a qualidade da energia elétrica o qual recebem. As principais atividades de monitoramento realizadas para a caracterização de problemas relacionados a qualidade de energia em um sistema de potência são detecções e classificações de distúrbios, além da compreensão dos dados, estimação e extração de parâmetros. Ainda, engloba fatores como localizar e identificar as fontes geradoras de distúrbios. Para tal, novas tecnologias em processamento digital de sinais, microprocessadores e dispositivos de armazenamento de dados, tornam possível o desenvolvimento de sistemas de monitoramento [22,25].

No mercado de energia elétrica, os sistemas de gestão de energia melhoram com a internet das coisas (IoT, do inglês Internet of Things). Empresas do setor de energia usam energias de fontes renováveis e estratégias baseadas na comparação de dados de indicadores de consumo dos equipamentos elétricos [26,27]. As tecnologias de energia considerada limpa e renovável promovem a sustentabilidade ambiental e os dispositivos inteligentes permitem um parecer imediato sobre o consumo de energia, o que aumenta a consciência sobre o estado da rede elétrica [27,28]. Segundo Golpîra e Bahramara [25] as redes inteligentes podem controlar os equipamentos de geração, transmissão, distribuição e consumo através da coleta de informações de indivíduos. Onde o desenvolvimento da tecnologia IoT torna possível transferir informações de demanda de energia do cliente para a nuvem, assim o banco de informações é armazenado em um servidor e toda rede de distribuição pode ser controlada.

3 Metodologia

A primeira fase da pesquisa parte da formação da *string*, o qual primou pelo desenvolvimento do protocolo de revisão e sua execução nas bases de dados. A partir da questão da pesquisa "Quais fatores influenciam na qualidade do fornecimento de energia elétrica utilizada em uma empresa? ", leituras iniciais auxiliaram para definição das palavras-chaves relacionadas ao desenvolvimento da *string* de busca. Duas bases de dados foram selecionadas: Spocus (Elsevier) e Web of Science (Clarivate Analytics). Essas bases, apresentaram as pesquisas mais relevantes da área de energia. Na estratégia de busca para a realização do estudo não foram especificados idioma e data de publicação, a única restrição aplicada foi a de artigos com acesso aberto. O desenvolvimento da pesquisa pode ser observado na Fig 2.

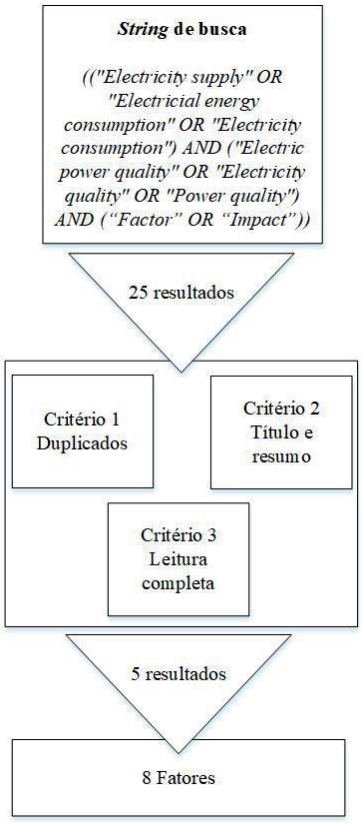

Fig. 2. Desenvolvimento da pesquisa

Na Fig. 2 é possível observar que a *string* de busca apresenta uma combinação de palavras presentes na questão da pesquisa, o que resultou em 25 artigos. A partir disso, foram aplicados os critérios de exclusão e extração. Primeiramente, no Critério 1, foram

excluídos os artigos duplicados, sendo identificado apenas um artigo. Na sequência, os demais critérios buscaram selecionar artigos de acordo com a questão da pesquisa.

No Critério 2 foram então selecionados 8 artigos a partir da leitura do título e resumo de todos os artigos. Já no Critério 3, foi realizada a leitura completa dos artigos selecionados no critério anterior, totalizando 5 artigos. Por fim, foi possível obter os fatores que influenciam na qualidade do fornecimento de energia elétrica utilizada em uma empresa. Assim, a metodologia empregada resultou em 8 fatores que respondem ao questionamento da pesquisa.

4 Resultados

Tendo em vista a importância da energia elétrica para a vida das pessoas, produção de bens e serviços em empresas, bem como a geração de empregos e contratos entre geradores e distribuidoras, a qualidade de toda essa energia consumida deve ser medida, analisada e monitorada. Para isso, faz-se necessário o conhecimento de fatores que influenciam este desempenho, sejam eles internos à organização, passíveis de melhoria como novas tecnologias e equipamentos, ou externos, como fatores ambientais ou ainda aqueles de domínio das empresas distribuidoras.

No Quadro 1 estão apresentados os cinco estudos encontrados e analisados, dos quais foram extraídos os 14 fatores que influenciam na qualidade do fornecimento de energia elétrica, com seus respectivos autores, título e ano de publicação.

Quadro 1. Estudos e fatores que influenciam na qualidade de energia elétrica

Título do Artigo	Autores	Fatores
Analysis of energy losses reduction potential on the distribution line of campus building through electric power quality improvement	Pawawoi et al. [15]	Perdas na linha de distribuição
		Equipamentos eficientes
		Investimento em automação
Analysis and identification of power blackout-sensitive users by using big data in the energy system	Shuai et al. [29]	Blecautes de energia
Performance analysis of methods at estimating insulated cables degradation	Velasco et al. [30]	Condições operacionais de equipamentos
Monitoring hydropower reliability in Malawi with		Mix de geração de energia

satellite data and machine learning	Falchetta, Kasamba e Parkinson [16]	Opções de backup
Analysis of the Spanish industry economical losses due to interruptions in the electricity supply	Coll-Mayor, Pardo e Pérez-Donsión [31]	Picos de consumo

Um dos principais fatores que afetam diretamente na qualidade da energia elétrica são as perdas de energia nas linhas de distribuição. Essas perdas reduzem significativamente a quantidade de energia que chega aos consumidores, reduzindo consequentemente, o seu consumo [15]. Essas perdas representam a diferença entre a energia injetada na rede de distribuição e a quantidade de energia que é faturada, sendo elas perdas técnicas e não técnicas [32]. As perdas técnicas ocorrem devido às perdas de calor nos componentes dos sistemas de transmissão e distribuição [33]. Já as perdas não técnicas, também conhecidas como perdas comerciais, dizem respeito as perdas não naturais e estão associadas a eletricidade não faturada e a faturada que não é paga, podendo ocorrer por erros na medição ou faturamento, ou comportamentos fraudulentos de consumidores [34], sendo muito difíceis de prever [35]. Com um plano de gerenciamento e investimentos em sistemas de automação é possível que consumidores e distribuidoras tenham um maior controle sobre essas perdas que ocasionam em desperdícios, sendo este um meio importante para aumentar a eficiência na distribuição e consumo [15].

Dispositivos inteligentes e sensores da Internet das Coisas, como medidores, terminais, equipamentos de monitoramento, dispositivos de telemetria e concentradores de dados, tem sido cada vez mais implementado nas redes de energia, fornecendo um grande suporte de dados para entender as características de cada usuário, proporcionando assim um aumento na qualidade da energia [29]. Esse ecossistema tecnológico, promete grandes redes de dispositivos conectados e coletando grandes volumes de dados e informações, monitorando fortemente os setores de energia [37]. Através do desenvolvimento e implementação desses dispositivos, os consumidores e as empresas responsáveis pela distribuição da energia, estarão mais preparadas para identificarem os motivos de uma queda na qualidade do fornecimento de energia elétrica, possibilitando um reparo imediato de eventuais falhas e evitando grandes perdas e prejuízos.

Outro fator que afeta a qualidade da energia, é o uso de equipamentos mais eficientes. Sendo de extrema importância que os consumidores se atentem a compra ou substituição de equipamentos ineficientes, isso trará um maior aproveitamento da energia elétrica, visto que a eficiência energética tem por definição a entrega de um trabalho considerando o mínimo de dispêndio possível [15]. A ineficiência energética está relacionada ao fato de os usuários utilizarem aparelhos antigos e ineficientes, sendo uma saída a este problema, o desenvolvimento de regulamentações que incentivem mudanças de hábitos por parte da população e à compra de novos equipamentos de alta eficiência [36].

Os chamados blecautes, ou quedas de energia, são outro fator que devem ser levados em consideração, pois afetam a qualidade da energia em todos os consumidores, sejam eles de maior ou menor curva de carga. Alguns aspectos devem observados, como tipos de sensores, duração de interrupções, perdas econômicas e localização como área urbana ou rural, afetarão no grau de sensibilidade de cada consumidor a esses blecautes de energia [29]. Essas quedas ou apagões de energia que afetam uma grande parte das redes de distribuição, são efeitos de falhas em cascatas, onde um componente afetado causa a falha de outros na sequência [38]. Esses apagões podem ser amenizados realizando investimentos para modernização dos elementos presentes na rede elétrica através do aumento de suas capacidades. Quedas de energia podem gerar extensas interrupções no fornecimento, gerando custos e prejuízos irreparáveis aos consumidores.

Os autores Velasco et al. [30] colocam que, garantir um fornecimento de energia confiável e de qualidade aos consumidores é um grande desafio, influenciando diretamente na melhoria de índices de continuidade da energia, como a duração e a frequência das interrupções. As condições operacionais dos equipamentos têm uma grande influência no sistema elétrico, como transformadores e cabos de energia. Sendo importante um sistema de monitoramento por software para realizar medições e o diagnóstico das condições operacionais dos equipamentos, objetivando reduzir interrupções de energia por falhas desses componentes.

Outro fator muito importante à qualidade da energia em um país é a diversificação da matriz elétrica. Países com grande dependência de recursos advindos de fontes renováveis para geração de energia, como ocorre por exemplo com o Brasil, o qual possui grande parte da energia proveniente usinas hidráulicas, acabam sofrendo com perturbações causadas por alterações climáticas, como longos períodos de estiagem ou enchentes, resultando em quedas de energia e apagões. Sendo assim, a capacidade adaptativa do país à novas fontes para geração de energia é de extrema importância para garantir qualidade de energia à toda população [16], possibilitando o suprimento de toda energia contratada mesmo que esses riscos e incertezas ocorram. Além disso, opções de backup seriam uma solução à países com o mesmo sistema de geração de energia brasileiro, viabilizando o armazenamento de parte ou de toda energia gerada para utilização em períodos de racionamento ou demais eventualidades, o que garantia qualidade no fornecimento de energia aos consumidores. Ainda externo às organizações, a quantidade de linhas de transmissão internacionais poderiam ser uma opção para garantir fornecimento de energia confiável, as importações de energia elétrica poderiam ser uma saída para eventuais problemas no sistema de abastecimento [16].

Por fim, os autores Coll-Mayor, Pardo e Pérez-Donsión [31] discutem em relação aos picos de consumo de energia elétrica nas indústrias, relatando que nesses períodos de máximo consumo ocorre uma maior perda de energia, afetando diretamente na qualidade. O estudo dos autores discute ainda sobre o desenvolvimento de uma metodologia que utiliza dados estatísticos para avaliar as consequências e perdas econômicas devido aos problemas de qualidade de energia, estes afetados por interrupções na fonte de alimentação ou quedas de tensão. Sendo as principais vantagens da nova metodologia a fácil aplicação, utilização de dados disponíveis,

desenvolvimento em diferentes países e o fornecimento de resultados para qualquer segmento de indústria.

5 Conclusões

Independente da sua causa, uma baixa qualidade de energia pode gerar perdas significativas aos consumidores. O termo qualidade na energia elétrica abrange toda cadeia de fornecimento e é importante desde a geração até a transmissão e distribuição da eletricidade. Com base nesse cenário, através da utilização do método de revisão sistemática de literatura foi possível identificar cientificamente fatores que afetam a qualidade da energia elétrica. Os autores citados neste estudo abordam metodologias que foram empregadas com a finalidade de avaliar problemas dentro do enquadramento de qualidade de energia elétrica.

Tendo em vista a importância do tema proposto e a carência de artigos que apontem aspectos gerais da falta de qualidade de energia nas organizações, este estudo foi realizado para elucidar e apontar soluções que auxiliem os consumidores no controle pela qualidade da energia elétrica. O conhecimento dos fatores internos torna possível às organizações traçar um plano de gerenciamento da qualidade, fazendo com que hajam investimentos em tecnologias, melhorando a produção e diminuindo gastos advindos desse consumo. Já a identificação de aspectos externos, como aqueles vinculados às empresas de distribuição e até mesmo climáticos, permite que as empresas saibam questionar aos responsáveis pelo setor de energia as medidas cabíveis para o melhoramento da qualidade da energia elétrica que chega até seus empreendimentos.

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Diseño de una red de domicilios en tiendas de barrio para abastecimiento de alimentos en tiempos de COVID-19: Un enfoque de optimización lineal

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Resumen. Este artículo tiene como objetivo la implementación de un modelo de localización de instalaciones para analizar el uso de los domicilios en el canal tradicional (tiendas de barrio) para mejorar la cobertura de la demanda de frutas y verduras con los cambios que ha supuesto la emergencia sanitaria causada por el COVID-19. Este tema presenta una gran relevancia dadas las restricciones de distanciamiento social y movilidad implementadas por muchos gobiernos para disminuir el contagio y garantizar la seguridad alimentaria de la población. El modelo busca la mejor configuración espacial de tiendas habilitadas para domicilios que incremente el acceso y la disponibilidad a las frutas y verduras. Se usó como caso de estudio los municipios de Chía y Cajicá en la región central de Colombia. Los resultados muestran que no es necesario más del 40% de tiendas habilitadas con servicio de domicilio para lograr la cobertura geográfica de las zonas críticas que son las áreas periféricas. Sin embargo, para incrementar la cobertura de la demanda si es necesario habilitar en más del 50% de tiendas el servicio de domicilio.

Palabras clave: Domicilios, problema de localización de instalaciones, logística de alimentos, tiendas de barrio, COVID-19.

1 Introducción

Desde que comenzó el brote del COVID-19 en enero de 2020 se han presentado más de 14 millones de casos y 597 mil muertes a nivel global. El brote se ha extendido por más de 200 países, siendo Colombia una de las naciones afectadas en donde hay más de 182 mil casos y 6 mil muertes [1]. Como solución para combatir la enfermedad, la mayoría de las naciones han reglamentado el confinamiento para disminuir la cantidad de contagios. Sin embargo, esto ha generado grandes impactos en la economía y el desarrollo del comercio [2], [3].

Las restricciones que ha impuesto la pandemia han representado un reto logístico sin precedentes y una gran disrupción en las cadenas de suministro (CS) [4]. Esto ha traído un gran riesgo para las operaciones, incluyendo cambios en la demanda, en la

distribución y en el abastecimiento [5]. El sector de "*retail*" ha sido uno de los más afectados; puesto que, para garantizar el acceso a los alimentos, ha tenido que buscar soluciones rápidas para responder a los cambios del comportamiento de los consumidores causados por las políticas adoptadas por los gobiernos durante la cuarentena [6].

De los factores que más han afectado la demanda a nivel general han sido el distanciamiento social y las restricciones de movilidad [7]. Específicamente, en el sector de alimentos, estas limitaciones han implicado la generación de las compras de pánico y el incremento de las compras online [8]. De hecho, este último efecto ha causado que muchos retailers hayan implementado el canal de domicilios para mejorar sus ventas por el efecto del COVID-19 [6]. Esto es debido a que se ha demostrado que la distancia es uno de los factores más importantes a la hora de que un cliente decida donde comprar sus alimentos [9], por ello garantizar el acceso y la disponibilidad es vital para sobrevivir a los efectos económicos de las restricciones antes mencionadas. Es así como los domicilios son una gran oportunidad para tratar con este problema [3].

Los domicilios son una parte importante del comercio electrónico, siendo especialmente complejo para los retailers al incrementar el ambiente tecnológico y así, las operaciones logísticas para la distribución de última milla [10]. Adicionalmente, la gestión de varios canales de ventas representa un reto para quienes solo han manejado las ventas presenciales. Es por lo que, la transformación inmediata a la que se tuvieron que someterse los retailers, dada la emergencia sanitaria, llevo a distintas ineficiencias [11].

Considerando lo anterior, el diseño de una red de domicilios se convierte en una decisión estratégica importante para que tenga el impacto deseado en el acceso a alimentos. Esto permite evaluar la disponibilidad que un hogar puede tener para abastecerse [12] y de esta manera, garantizar su seguridad alimentaria especialmente en tiempos de emergencia. Por estas razones, el presente artículo propone un modelo de optimización lineal entera mixta (MILP, por sus siglas en inglés) para diseñar una red de domicilios de tiendas que permita mejorar el acceso a alimentos frescos en los municipios de Chía y Cajicá, Colombia. Las tiendas en Colombia han sido el principal medio de abastecimiento en el tiempo de cuarentena. Estas han incrementado hasta en 96% sus ventas [13], [14]. Teniendo en cuenta esto y que el comercio online ha crecido significativamente [15], la red de domicilios garantizaría la supervivencia de este canal de retail a pesar de las implicaciones económicas de la pandemia; ya que, agrega valor a la CS [10]. Adicionalmente, se seleccionan los alimentos frescos, específicamente las frutas y verduras, teniendo en cuenta su importancia para garantizar la seguridad alimentaria del área de estudio; dado que, actualmente hay un bajo consumo de estas [30].

Este artículo está organizado como sigue. La sección 2 muestra los antecedentes de este trabajo con una breve revisión de los conceptos involucrados. La sección 3 presenta la definición formal del problema y el modelo matemático asociado. La sección 4 describe el caso de estudio de los municipios de Chía y Cajicá y el uso del modelo propuesto. La sección 5 presenta los resultados principales de la implementación en el caso de estudio. Finalmente, la sección 6 discute las conclusiones de este trabajo y sugiere algunos trabajos futuros.

2 Antecedentes

En esta sección se dará una breve revisión de los conceptos requeridos para el desarrollo de este trabajo.

2.1 Disrupción en CS causadas por pandemias

El efecto de las pandemias sobre las CS ha sido especialmente estudiado desde el punto de vista de logística humanitaria [16], [17]. No obstante, gran parte de estas investigaciones han sido enfocadas en mejorar la capacidad de respuesta para el suministro de dotaciones y recursos médicos. Por ejemplo, He et al. [18] presentaron un nuevo modelo de programación lineal para una rápida respuesta de los servicios médicos para tratar con emergencias sanitarias. Por otro lado, Anparasan et al. [19] propusieron un modelo de analítica de datos para asignar los recursos médicos en países en desarrollo usando información de la epidemia de cólera en Haití en 2010.

Sin embargo, hay pocas investigaciones asociadas al impacto económico y comercial de una pandemia sobre las CS. Chou et al. [20] son de los pocos autores que han investigado estos efectos con el virus del SARS en 2004 encontraron que el impacto más grande para Taiwán fue en el sector aéreo. Otros autores fueron Calnan et al. [21] quienes analizaron el efecto del virus del ébola en África en aspectos sociales y económicos concluyendo que construir un sistema de apoyo es importante para tratar los efectos de las pandemias.

Recientemente, con el brote del COVID-19 han aparecido nuevas investigaciones; dado que, muchos países cerraron sus fronteras causando grandes impactos en el comercio [5]. Un ejemplo de estos estudios son los llevados a cabo por Ivanov [5], [22] quien ha estudiado los factores que se requieren para tener una CS resiliente y predecir los efectos a largo plazo con simulación. Esto lo ha hecho a nivel general, mientras que Nicola et al. [8] han descrito específicamente los impactos en cada área económica. Para el caso del área de alimentos ha mencionado el incremento en los domicilios, siendo una parte importante para mantener la economía que debe ser regulada. Al respecto Li et al. [6] realizaron una encuesta en Wuhan en la cual se confirmó que el comercio online predominaba para abastecerse de alimentos. Sin embargo, está medida ha sido adoptada en distintos países sin una planeación previa teniendo en cuenta que es parte de una toma de decisiones estratégica.

2.2 Modelos de localización para el diseño de redes de domicilios

Habilitar los domicilios es una decisión estratégica importante, ya que implica un rediseño de la CS [12]. Una de las herramientas para tratar este problema son los modelos matemáticos de MILP, específicamente el problema de localización de instalaciones (FLP, por sus siglas en inglés). Este modelo consiste en la selección de la localización de una o más instalaciones para atender la demanda de un conjunto de consumidores [23]. Para el caso específico de los domicilios la mayor parte de los estudios se han concentrado en las decisiones tácticas de la distribución. Por ejemplo, Cagliano et al [24] utilizaron dinámica de sistemas para analizar el flujo en la CS

completa y optimizar la ruta de distribución según el tráfico en tiempo real. Los resultados mostraron la eficiencia de utilizar herramientas tecnológicas para la distribución de última milla. Autores como Pan et al. [25], Chen et al. [26] y Aktas et al. [27] usaron modelos matemáticos de ruteo de vehículos para disminuir costos operacionales, distancias y así tener mejor eficiencia en la distribución. En el alcance de esta investigación, solo se encontraron dos estudios que trataron con habilitar domicilios en los puntos de abastecimiento. El primero realizado por Zambetti et al. [12] quienes utilizaron un modelo de localización de instalaciones para asignar las localizaciones de los depósitos de las empresas intermediarias que prestan el servicio de domicilios. El segundo hecho por Hong et al. [28] también asignaba depósitos de envío desde donde se iniciaba el proceso de domicilio y adicionalmente optimizaban la ruta a seguir. No obstante, ninguno de estos modelos habilitaba el servicio de domicilio directamente en el punto de venta según la cobertura geográfica y por esta razón, es que este trabajo busca dar una solución al problema teniendo en cuenta las restricciones de movilidad dadas por la pandemia del COVID-19.

3 Propuesta

En esta sección se presenta en primer lugar la definición formal del problema del diseño de la red de domicilios y, en segundo lugar, se muestra el modelo matemático de programación lineal entera mixta (MILP, por sus siglas en inglés) asociado al problema.

3.1 Modelo MILP

La definición del problema es enunciada como sigue:

Un conjunto de clientes (hogares) $H = \{1...j\}$ se consideran geográficamente distribuidos dentro del área de estudio según la densidad residencial y deben abastecerse de alimentos frescos. Cada hogar $j \in H$ tiene una demanda d_j que debe ser satisfecha por una tienda $R = \{1...i\}$ dentro la máxima distancia de cobertura para el canal de ventas (presencial o domicilios) $V = \{1...k\}$ definido por el parámetro a_{ijk}. La capacidad de cada tienda $i \in R$ tiene un límite dado por el parámetro Q_{ik} para cada canal de ventas $k \in V$. Se considera que hay un ingreso P_1 por cada hogar $j \in H$ que este dentro del rango de cobertura de cada tienda $i \in R$ y otro ingreso P_2 por cada kilogramo de la demanda de un hogar $j \in H$ abastecido por la tienda $i \in R$. Adicionalmente, existe un costo C_k por habilitar el canal de ventas $k \in V$. Finalmente, tuvimos en cuenta un número máximo N de tiendas que pueden habilitarse para tener domicilios y un mínimo porcentaje β de la demanda total de alimentos frescos a cubrir.

3.2 Formulación del modelo

La siguiente notación es usada para formular el modelo de FLP:

Conjuntos

H conjunto de hogares; $j \in H$
R conjunto de tiendas potenciales para habilitar domicilios; $i \in R$
V conjunto de canales de ventas ofrecidos en las tiendas; $k \in V$

Parámetros

d_j demanda esperada para el hogar j
Q_{ik} máxima capacidad habilitada para cada tienda i en el canal de ventas k
a_{ijk} parámetro binario donde es 1 si la tienda i cubre al hogar j en el servicio k y 0 en otro caso
P_1 ingreso por cubrir espacialmente a un hogar
P_2 ingreso por kilogramo cubierto de la demanda de frutas y verduras
C_k costo por habilitar el canal de ventas k
N Porcentaje máximo de tiendas que pueden habilitarse para tener domicilios
t Total de tiendas que pueden habilitarse para tener domicilios
β mínimo porcentaje de la demanda total de frutas y verduras por cubrir
M número suficientemente grande para restricciones lógicas

Variables de decisión

$X_{ik} = \begin{cases} 1 \text{ Si la tienda } i \text{ utiliza el canal de venta } k \\ 0 \quad \text{En otro caso} \end{cases}$

$Y_{jk} = \begin{cases} 1 \text{ Si el hogar } j \text{ está cubierto en el canal de venta } k \\ 0 \quad \text{En otro caso} \end{cases}$

Z_{ji}= Proporción de la demanda del hogar j cubierto por la tienda i

La formulación es como sigue:

$$Max \sum_{j\in H}\sum_{k\in V} P_1 Y_{jk} + \sum_{i\in R}\sum_{j\in H} P_2 d_j Z_{ji} - \sum_{i\in R}\sum_{k\in V} C_k X_{ik} \quad (1)$$

Sujeto a:

$$\sum_{i\in R} a_{ijk} X_{ik} \geq Y_{jk} \quad \forall j,k \; ; \; j \in H, k \in V \quad (2)$$

$$\sum_{i \in R} a_{ijk} X_{ik} \leq M \, Y_{jk} \quad \forall j,k \; ; \; j \in H, k \in V \quad (3)$$

$$Z_{ji} \leq \sum_{k \in V} a_{ijk} X_{ik} \quad \forall i,j \; ; \; i \in R, j \in H \quad (4)$$

$$\sum_{i \in R} Z_{ji} \leq 1 \quad \forall j \; ; \; j \in H \quad (5)$$

$$\sum_{i \in R}\sum_{j \in H} d_j Z_{ji} \geq \beta \sum_{j \in H} d_j \quad \forall t \; ; t \in T \quad (6)$$

$$\sum_{j \in H} d_j Z_{ji} \leq \sum_{k \in V} Q_{ik} X_{ik} \quad \forall i \; ; \; i \in R \quad (7)$$

$$X_{ik} = 1 \ \forall i, k = 1 \ ; i \in H, k \ \in V \quad (8)$$

$$\sum_{i \in R} X_{ik} \leq N * t \ \ \forall k = 2 \ ; \ k \in V \quad (9)$$

$$Z_{ji} \geq 0 \ \ \forall j, i \ ; \ i \in R, j \in H \quad (10)$$

$$X_{ik} \ , Y_{jk} \ \in \{0,1\} \ \forall i, j, k \ ; \ i \in R, j \in H, k \ \in V \quad (11)$$

La función objetivo (1) maximiza la utilidad total de las tiendas teniendo en cuenta los ingresos por cubrir una tienda, los ingresos por las ventas de frutas y verduras y el costo que tiene habilitar el servicio de domicilios. El conjunto de restricciones (2) y (3) establece que un hogar puede estar cubierto en un canal de venta si este está dentro del rango de cobertura de una tienda que ofrece ese canal. El conjunto de restricciones (4) asegura que la demanda de un hogar solo puede estar cubierta por una tienda que tenga habilitado un determinado canal de venta y este dentro del rango de cobertura de esa tienda. El conjunto de restricciones (5) garantiza que la demanda de un hogar no se puede cubrir en más del 100% El conjunto de restricciones (6) asegura que la proporción cubierta de la demanda de frutas y verduras es mayor o igual que el porcentaje fijado previamente. El conjunto de restricciones (7) evita que las ventas de las tiendas sean mayores que sus capacidades. El conjunto de restricciones (8) habilita el servicio presencial para todas las tiendas, mientras que el conjunto de restricciones (9) limita el número de tiendas a las que se les puede habilitar el canal de ventas de domicilios. Finalmente, el conjunto de restricciones (10) y (11) hacen referencia a la naturaleza de las variables de decisión de no-negatividad y binarias.

4 Descripción del caso de estudio

Para este estudio se usaron datos recolectados de los municipios de Chía y Cajicá. Ambos son municipios colombianos los cuales pertenecen al departamento de Cundinamarca ubicados en la provincia Sabana Centro, a 10 y 17 km al norte de la ciudad de Bogotá (capital de Colombia), respectivamente. Chía tiene 142,302 habitantes [35], mientras que en Cajicá hay 62,862 habitantes [36]. Ambos municipios representan aproximadamente el 30% del territorio geográfico de la región.

En esta área la malnutrición prevalece evidenciándose en las tasas de niños nacidos con bajo peso, siendo de aproximadamente 11.2%, cifra que es preocupante [29]. Uno de los factores que más afecta es el bajo consumo de frutas y verduras [30] que en Colombia es de aproximadamente 190 gramos por persona, mientras que lo recomendado por la OMS es de 400 g [31]. El abastecimiento de alimentos en la zona tiene grandes fallas logísticas, por ejemplo los costos de transporte son elevados, el tiempo para abastecerse es alto al ir hasta Bogotá, la falta de planeación en el manejo de inventarios, entre otras [32]. Esa falta de planeación hizo que con la llegada del COVID-19 muchas tiendas no pudieran responder al incremento de la demanda y a la búsqueda de canales alternativos por el confinamiento [6].

4.1 Preparación de los datos

Los puntos demanda se establecieron ubicando la densidad poblacional del área a través de Google Earth™. Para Chía se tomaron 700 puntos de demanda, mientras que para Cajicá se tomaron 495 puntos. Con la información obtenida de la población de ambos municipios se asumió que cada punto en Chía representaba a 203.3 habitantes, mientas que para cada punto en Cajicá representaba a 127 habitantes. El consumo por persona se determinó mediante el Perfil Nacional de Consumo de Frutas y Verduras [37], en el cual, para el departamento de Cundinamarca, la media de consumo de frutas y verduras (alimentos frescos) fue de 107 gr y 107.8 gr respectivamente; por lo que, se asumió que el consumo total en los municipios de Chía y Cajicá es de 0.2148 Kg por persona. Con lo anterior se determinó que para cada punto de demanda el consumo es de 305.665 Kg por semana para el municipio de Chía y para Cajicá cada punto de demanda consume 190.948 Kg por semana.

Por otro lado, el número potencial de tiendas de barrio que existen en ambos municipios se determinó a través de las vistas panorámicas proporcionadas por Google Earth™ y Google Maps™. Se obtuvo que el municipio de Chía cuenta con un aproximado de 144 tiendas y el municipio de Cajicá cuenta con 104 tiendas aproximadamente. Las distancias fueron calculadas con la ecuación de Haversine, la cual da la distancia de dos puntos en una esfera según su la latitud y longitud [33]. Para considerar la estructura vial y otras condiciones geográficas se consideró un factor multiplicador [34]. El radio máximo de cobertura del servicio presencial es de 0.5 kilómetros mientras que el de servicio de domicilio es de 2 kilómetros.

Para conocer la capacidad de las tiendas, se realizaron 74 encuestas a tenderos. En la Tabla 1 se presentan los resultados de frecuencia y de cantidad de compra. Se puede observar que el 51% de los tenderos se abastecen de 2 a 3 veces por semana, y el 22% compran entre 151 y 180 kg cada vez que se abastecen. Por esta razón, la capacidad se determinó con el promedio del consolidado entre la frecuencia de compra y la cantidad de compra para cada municipio. A partir de esto se obtuvo un promedio total semanal de 672 Kg para todas las tiendas ubicadas en Chía y de 415 Kg para las tiendas ubicadas en Cajicá. Asumimos que para habilitar domicilios es necesaria una capacidad adicional de un 15%.

Tabla 1. Resultados de frecuencia y cantidad de compra de la encuesta aplicada a tenderos

Frecuencia de compra	%	Cantidad por cada compra	%
2-3 veces por semana	51%	Más de 180 kg	34%
Diariamente	27%	151-180 kg	22%
1 vez a la semana	16%	31-60 kg	19%
4-6 veces por semana	5%	91-120 kg	11%
Menos de una vez a la semana	1%	61-90 kg	7%
		Menos de 30 kg	4%
		121-150 kg	4%

El ingreso asociado a que un hogar se encuentra cubierto por alguna tienda es de $82,500 COP ($22.1 USD aprox.) y hace referencia al precio por semana de la canas-

ta básica familiar [38]. Por otro lado, el ingreso relacionado a la venta de frutas y verduras es de $3,500 COP ($1 USD aprox.) por kilogramo, el cual se tomó teniendo en cuenta el precio de abastos del boletín de precio diario [39]. Para el costo de habilitar un determinado tipo de venta, se asumió que para venta presencial es de $0 COP, al ya existir las tiendas, y para la venta por domicilio un costo asociado al tiempo que le tomaría a un domiciliario realizar el recorrido de la tienda hasta el punto de demanda según el salario mínimo legal vigente de Colombia año 2020 [40], obteniendo un costo de $714,000 COP ($192 USD).

5 Resultados

El modelo matemático fue implementado en el software GAMS. Probamos diferentes instancias con la variación del número máximo de tiendas N que se habilitarán para tener domicilios y el porcentaje mínimo a cubrir de la demanda total de frutas y verduras β. El parámetro N se varío de acuerdo con un porcentaje entre 20% y 70% del total de tiendas que hay en Chía y Cajicá.

La Fig. 1 muestra la cobertura real de la demanda de frutas y verduras en los casos evaluados con un β de 0.1 y 0.5. Se puede observar como el porcentaje de cubrimiento de la demanda varía principalmente por la cantidad de tiendas N habilitadas para prestar servicio de domicilio sin importar el porcentaje mínimo de la demanda β definido para cada prueba de experimentación. De hecho, para β entre 5% y 40% la curva obtenida es la misma que es la mostrada en la Fig. 1 con un β de 0.1.

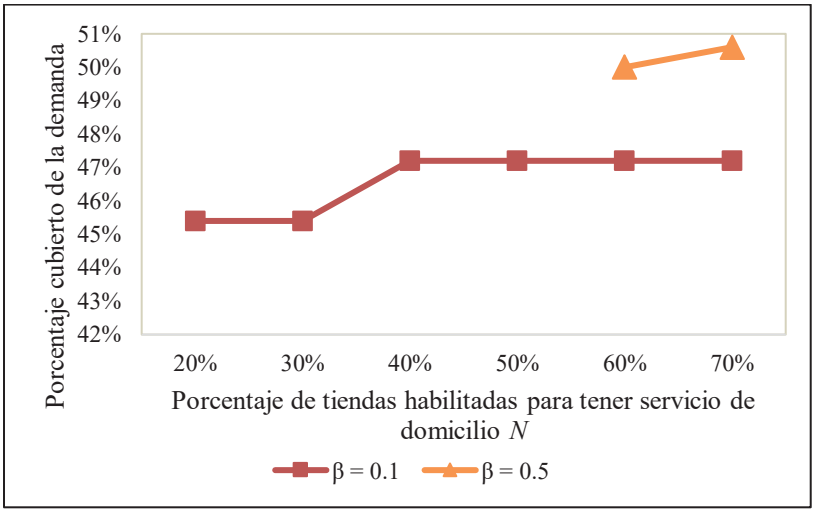

Fig. 1. Porcentaje real cubierto de la demanda de acuerdo con la cantidad de tiendas habilitadas para tener domicilios y el porcentaje mínimo a cubrir de la demanda total de frutas y verduras

Lo anterior se da debido a que la cobertura de la demanda que hay en cada uno de los casos depende de la capacidad con la que se cuenta acorde a las tiendas habilitadas

para tener servicio de domicilio. Observamos que el cubrimiento de la demanda se estabiliza luego de tener el 40% del total de las tiendas habilitadas para domicilios con un porcentaje mínimo de la demanda β de hasta 40%. Este es un resultado interesante que indicaría que el servicio de domicilio para más del 40% de las tiendas existentes no es necesario, ya que no varía el cubrimiento de la demanda. Sin embargo, para cubrir más del 50% de la demanda de frutas y verduras es necesario habilitar como mínimo un 60% de las tiendas existentes, lo cual implicaría mayores costos de implementación del servicio. Hay que tener en cuenta que no se están considerando los otros tipos de vendedores de frutas y verduras como supermercados mayoristas, mercados centrales, entre otros; por lo que, cubrir un 50% de la demanda estaría dentro de una buena solución al suponer que la cantidad restante es abastecida por los tipos de vendedores.

Por otro lado, el anterior patrón de estabilización del porcentaje real cubierto de la demanda se confirma con los resultados mostrados en la Tabla 2, en la cual se observa la cantidad de tiendas que es asignada para tener domicilios en cada caso evaluado. Podemos observar que el número de tiendas habilitadas para tener el canal de domicilios no supera las 75 para β menores a 40%. De hecho, este mínimo porcentaje de la demanda a cubrir no afecta el resultado hasta que se evalúa con 50%, donde se evidencia, tanto en la Fig. 1 como en la Tabla 2, que es necesario habilitar más de las 75 tiendas con el servicio de domicilio.

Tabla 2. Número de tiendas habilitadas para prestar el servicio de domicilios según las variaciones del parámetro N y el parámetro β

N	β =5%	β =10%	β =20%	β =30%	β =40%	β =50%
25%	9	9	9	9	9	
30%	9	9	9	9	9	
35%	75	75	75	75	75	
50%	75	75	75	75	75	
60%	75	75	75	75	75	148
75%	75	75	75	75	75	173

Por otro lado, frente al cubrimiento espacial, la Fig. 2 indica zonas con desabastecimiento en las periferias de ambos municipios (puntos rojos), exponiendo a los habitantes de esta zona al riesgo de contagio al tener que ir lejos de sus casas a hacer la compra de alimentos. Este cubrimiento es considerando solo el canal de ventas presencial en las tiendas.

Con las soluciones obtenidas con el modelo el cubrimiento espacial mejora. Por ejemplo, seleccionando la solución con un β de 40% y un N de 30%, se habilitan un total de solo 9 tiendas (Ver Tabla 2) con domicilios que se distribuyen geográficamente como se muestra en la Fig. 3 (a). Esta distribución logra el cubrimiento geográfico observado en la Fig. 4 en la cual se puede ver que se logra cubrir los puntos de demanda que no son cubiertos en el escenario actual en las áreas periféricas de ambos municipios (Ver Fig. 2) garantizando que todos los puntos de demanda están cubiertos

por al menos una tienda para abastecerse. Además, se obtiene una cobertura del 45.4% de la demanda de frutas y verduras.

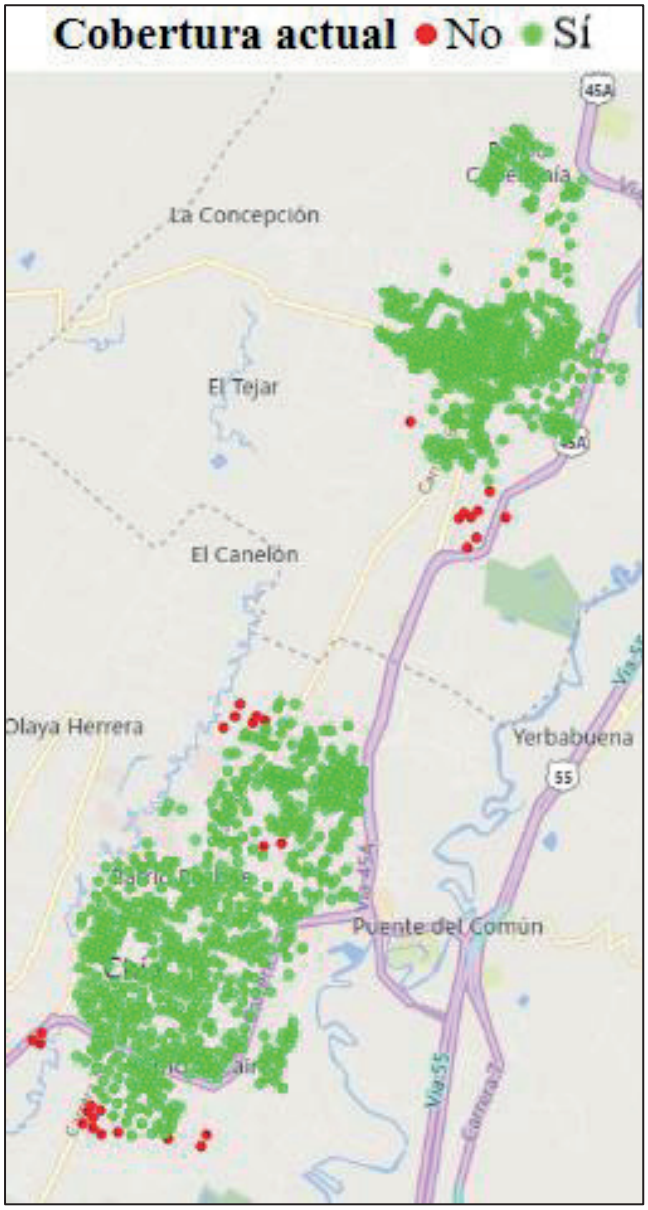

Fig. 2. Cobertura espacial actual de la demanda de frutas y verduras en Chía y Cajicá

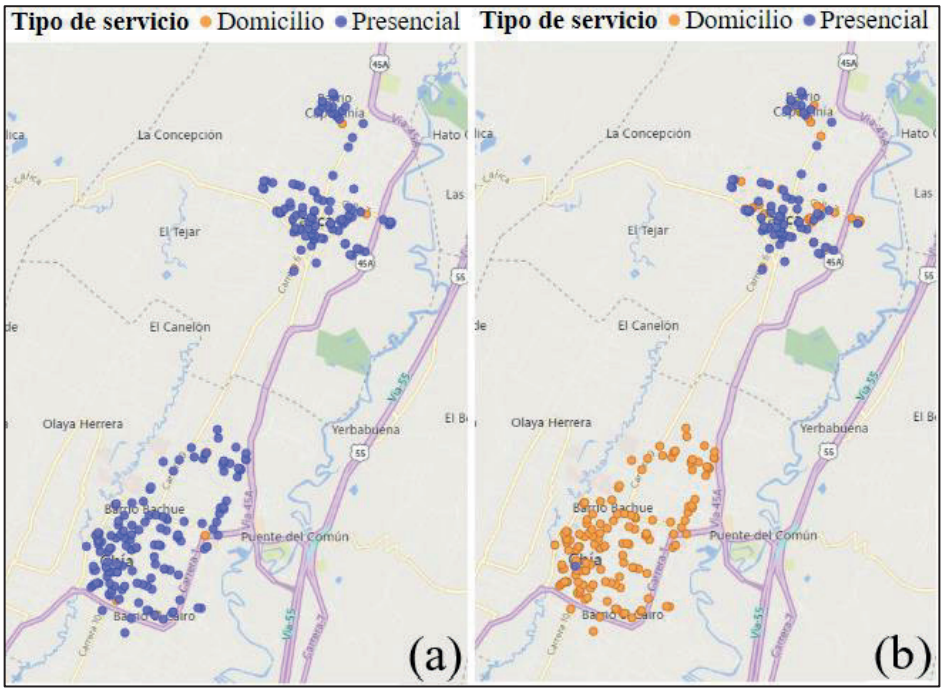

Fig. 3. (a) Tipo de servicio en cada tienda en escenario con un β de 40% y un N de 30%. (b) Tipo de servicio en cada tienda en escenario con un β de 50% y un N de 70%.

Seleccionando otro escenario para analizar la cobertura; por ejemplo, la solución con un β de 50% y un N de 70%, en la cual se habilitan un total de 173 tiendas con domicilios (Ver Tabla 2) que se distribuyen geográficamente como se muestra en la Fig. 3 (b), la cobertura que logra esta distribución es la misma mostrada en la Fig. 4. Es decir que, aunque se logre que todos los puntos de demanda queden cubiertos por al menos una tienda ya sea presencialmente o por medio de domicilios, el cubrimiento geográfico no mejora. Esto evidencia que, para tener un buen acceso espacial al abastecimiento de frutas y verduras, no se requiere un gran número de tiendas con domicilios. Sin embargo, la cobertura de la demanda con esta solución se incrementa a 50.6%, un 5% más en comparación mostrado en la Fig. 3 (a), lo cual mejora la disponibilidad de frutas y verduras para la población. Así que, aunque no se mejore la accesibilidad espacial si se mejora la disponibilidad de la cantidad ofertada para suplir la demanda. Adicionalmente, esta solución permite que las personas de ambos municipios tengan mayores opciones para poder abastecerse debido a que serían muchas más las tiendas las que prestarían el servicio presencial y de domicilios. No obstante, el habilitar más domicilios genera costos individuales a cada propietario.

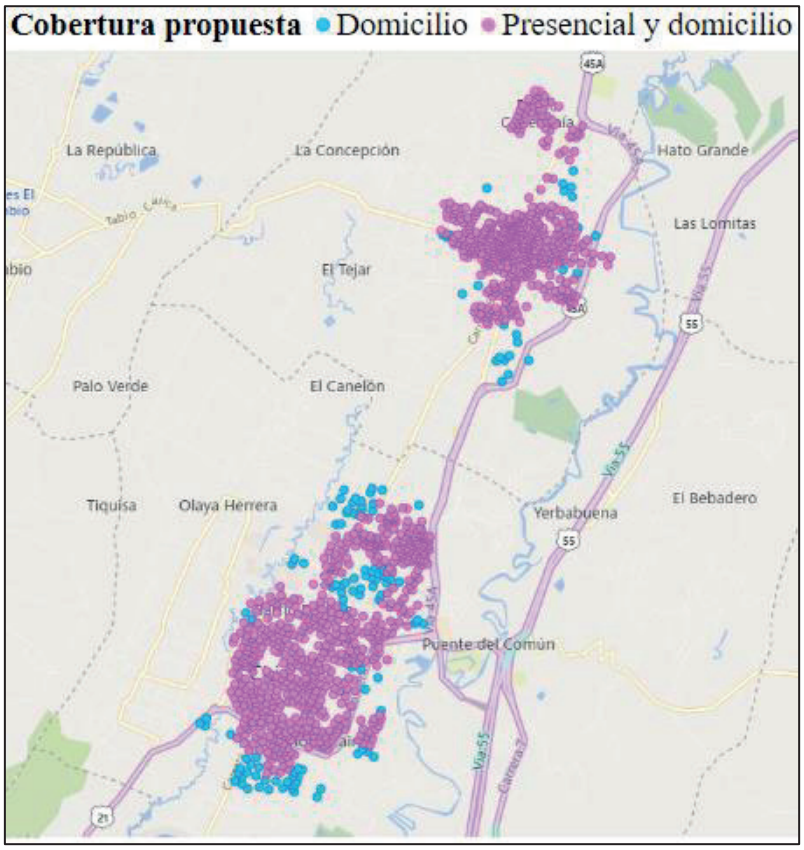

Fig. 4. Cobertura geográfica de la solución del escenario 1 y 4 según el tipo de canal de ventas para los municipios de Chía y Cajicá

6 Conclusiones y trabajos futuros

Esta investigación propuso una solución para la distribución de una red de domicilios de tiendas teniendo en cuenta la presencia del COVID-19 y las restricciones de confinamiento para evitar contagios. Con el modelo se logró determinar cuántas y cuáles tiendas son las que deberían ser habilitadas para prestar servicio de domicilio para que todos los puntos de demanda estuvieran cubiertos por lo menos por una tienda en cualquiera de sus modalidades (servicio presencial o domicilio).

Se observó que, a pesar de poder habilitar hasta el 70% de tiendas con domicilios, el modelo no lo hacía al obtener el cubrimiento geográfico de todos los hogares con solo el 40% del total de tiendas en las zonas de estudio. Esto se pudo observar en la Fig. 1, lo cual indica que no es necesario tener una red con más de 10 tiendas para mejorar la accesibilidad a frutas y verduras. No obstante, para cubrir más del 50% de la demanda total es necesario habilitar más de 140 tiendas con el servicio de domicilio, es decir que se requería mayor inversión para el aumento de la capacidad.

Considerando esto, dependiendo del enfoque de la necesidad que se desee suplir, ya sea en obtener la utilidad máxima o tener una mejor cobertura de la demanda total de frutas y verduras, se puede observar que una solución es mejor que otra a pesar de mantener la misma cobertura espacial. Hay que considerar los presupuestos limitados que pueden tener estas tiendas; ya que, las que se están analizando son tiendas de barrio que por su tamaño pueden restringirse de la posibilidad de prestar el servicio de domicilio. Para futuras investigaciones se puede considerar esa variación en el tamaño y presupuesto específico que tiene cada una de las tiendas; además de, la disposición de los hogares (clientes) a usar un tipo de servicio en lugar de otro.

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Study of the location of a second fleet for the Brazilian Navy: Structuring and mathematical modeling using SAPEVO-M and VIKOR methods

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Abstract. The Brazilian Navy's main mission is to control maritime areas, deny the use of the sea to the enemy and design the Naval Power, thus defending the Brazilian Jurisdictional Waters (BJW). For this, a robust naval force is needed to enable the fulfillment of its mission. The Brazilian Navy Fleet is located in the interior of Guanabara Bay, where the Port of Rio de Janeiro is also located. This fact weakens the National Defense since there is the possibility of carrying out, by ships, submarines, or mines enemies, a dam or blockade of the only exit to the sea. Therefore, this paper aims to select the most suitable city to be the headquarters of the Second Fleet of the Brazilian Navy. Several localities distributed throughout practically all navigable areas of the Brazilian territory were analyzed as possible headquarters for the Second Squadron. For the structuring of the problem, the Soft Systems Methodology (SSM) was used. For the decision-making process, hybrid modeling was used, with the SAPEVO-M method to obtain the weights of the criteria and the VIKOR method for the evaluation of alternatives. For the composition of the model, the criteria Distance to the Sea (KM), Width of Departure (KM), Distance from Rio de Janeiro (MN), Infrastructure for Repairs, and State of the Sea (Scale) were selected. After the application of the methods, the city of Belém was selected as the most indicated to be the headquarters of the new Brazilian Fleet.

Keywords: Management, Multicriteria Analysis, SAPEVO-M, VIKOR, Brazilian Navy.

1 Introduction

The National Defense Strategy (END), enacted in 2008 and updated in 2012, in order to ensure the security of the country both in peacetime and in crises, establishes guidelines for the proper preparation and training of the Brazilian Armed Forces (FFAA). The END was also developed to meet the equipment needs of the Military Commands, reorganizing the defense industry so that the most advanced technologies are under national control and instituting medium and long-term strategic actions aimed at modernizing the national defense structure [1].

Brazil's natural maritime vocation is supported by its extensive coastline, waterways, the magnitude of its maritime trade and the undeniable strategic and economic importance of the South Atlantic, which hosts the "Blue Amazon", an area that incorporates the high potential for living and non-living resources, such as Brazil's largest oil and natural gas reserves. The oceans are also important climate conditioners, besides serving as a cradle for submarine cables, whose data traffic is responsible for virtually all of the country's communication with the world [2].

The naval power must possess sufficient capacity and credibility to deter any adverse forces from conducting hostile actions in the AJB. The action of naval units in the South Atlantic, where the "Blue Amazon" is inserted, and in the Amazon and Paraguay rivers basins will be an essential factor for strengthening this deterrence. Thus, the Force must be prepared, both to act in an interstate crisis, and to monitor and suppress the actions of adverse groups practicing illegal activities in the AJB [2].

Over the past few years, much has been discussed about the constitution of the so-called Second Fleet, supported by a Naval Base capable of meeting the logistical needs arising. Numerous reasons justify a greater presence of the Brazilian Naval Power in the Blue Amazon [3].

With the survey of some points in the history of wars around the globe, there is a need to deal with some difficulties that Brazil may face if there is an armed conflict. An important point is a possibility of being carried out, by enemy ships or submarines, a dam or blockade at the exit to the sea. As Brazil has only one fleet headquarters – Rio de Janeiro – the country could go through serious problems due to the lack of a Second Fleet. Another important point, of great value to society, which justifies the Second Squadron, is the need for patrols and naval inspections, ensuring national sovereignty throughout the Blue Amazon.

However, the budgetary constraints are known and the need to prioritize the construction of submarines and corvettes, more essential to the Naval Power, led to the postponement of the Second Squadron project and its Naval Base [3].

In the study proposed by this paper, localities distributed through all navigable areas of the Brazilian territory are analyzed as possible headquarters for the Second Fleet.

In the decision-making process, Production Engineering becomes a fundamental mechanism in advising managers [4]. Part of this area, Operational Research (OR) is the comprehensive and multidisciplinary field that employs mathematical and analytical models for the solution of complex problems [5].

One relevant feature for a method of supporting decision-making is the availability of software implementing the method, as well as its graphical representation and

exploitation of results [6]. Considering the structure of the proposed problem and the availability of software, this article will use hybrid modeling composed of the SAPEVO-M method to obtain the weights of the criteria and VIKOR method for the evaluation of alternatives.

Taking into account that the country is undergoing a serious budgetary constraint, only cities that already have a previously established naval base structure will be evaluated, considering that the construction of a large maintenance complex requires a large amount to the public coffers.

2 Problem Structuring

Problems Structuring Methods (PSM) are one of the stages of the decision-making process that aims to organize issues, questions and/or dilemmas for which decision propositions are sought [7]. PSM is widely accessible in the OR and in the movement of systems for understanding and structuring complex problems [8].

Every model has validity only within a certain managerial context, which, in addition to taking into account the specificities of the organization studied, also has a "space-time" validity [9].

Among the most used PSM, this paper will use the Soft Systems Methodology (SSM) [10], which has been explored in a variety of research fields, as well as serves equally diverse practical interests.

SSM presents seven stages of application [10], which two will be addressed in this article for the problem structuring:

1 - explore an unstructured problematic situation; and

2 - express it by making a rich picture.

In the first stage, the brainstorming technique was used by the authors to demonstrate the perceptions of the group about all possible information, without interference or judgments to define the problem. In the second stage, a rich picture was constructed (Fig. 1) to express all relevant aspects of the problem.

The rich picture is a simple SSM tool, extremely useful for opening the discussion around individual perceptions towards a broad view of the different issues affecting the situation. They are created freely and unstructured to capture the participants' interpretation of a real situation [10,11].

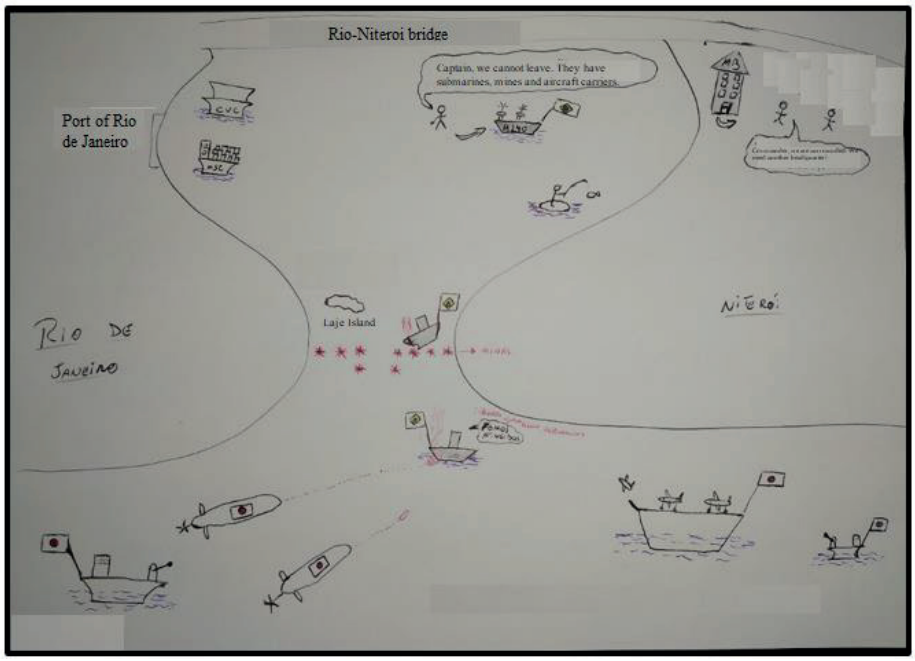

Fig. 1. Rich picture, entitled "Need for a second Fleet".

The rich picture shows that the Brazilian Navy Squadron is located inside Guanabara Bay, where the Port of Rio de Janeiro is also located. This fact weakens the national defense since there is the possibility of being carried out a dam or blockade of the only exit to the sea. This is considered a Political and Strategic movement that can lead Brazil to experience severe problems.

After analyzing the rich picture and consulting three Brazilian Navy officers with more than 20 years of experience, five criteria were established: Distance to the Sea (DS, Exit Width (EW), Distance from Rio de Janeiro by sea (DRJ), Infrastructure for Maintenance (IM) and State of the sea (SS).

Also, the alternatives of cities to be established as the headquarters of the second fleet were established, all of them with previously established naval base structure: Salvador/BA, Natal/RN, Rio Grande/RS, Ladário/MS, Belém/PA and Manaus/AM.

2.1 Presentation of criteria

The five criteria were chosen to compose the model are as follows:

I – Distance to the Sea (DS): It was considered to be the approximate distance of the existing Military Organizations, which could be reformulated to become the probable Second Squadron, to the point where it is considered the largest free area for maneuvering the naval means.

II – Exit Width (EW): The exit width to the sea is essential, since the smaller the maneuvering space, the greater the probability of applying some type of barrier or

blockade so that it is not possible to have access to the sea. Besides, a larger entry/exit width allows access to larger ships to the future second fleet headquarters.

III – Distance to Rio de Janeiro by sea (DRJ): Considering that the Brazilian coast is considerably extensive and taking into consideration the existence of a headquarter in Rio de Janeiro, the further away from this Second Squadron is, the better it will be for a larger area of operation concerning the protection of the entire Brazilian coast.

IV - Infrastructure for Maintenance (IM): It was considered as being the supply of specialized labor and bases for repairs of ships that will be crowded in the second fleet.

V - State of the sea (SS): Considered as being the general condition of ocean waves in a given locality and time. The state of the sea is characterized by statistics, which include wave height, frequency and spectral density. In this article, the data referring to the state of the sea were recorded by the official website of the Brazilian Navy Hydrography Center [12] through the Douglas Scale of the State of the Sea.

2.2 Presentation of alternatives

After the establishment of the criteria, and seeking to evaluate cities with previously established infrastructure, distributed along the Brazilian coast, six cities were selected to compose the model: Salvador - BA, Natal - RN, Rio Grande - RS, Ladário - MS, Belém - PA and Manaus - AM.

Table 1 presents the attributes of the cities in each criterion.

Table 1. Data from the cities evaluated.

Criterion	Feature	Salvador/ Ba	Natal	Rio Grande	Ladário	Belém	Manaus
DS (Km)	1st exit	1,7	5,5	18	No access	100	No access
	2nd exit	25	-	-	-	130	-
EW (m)	1st exit	450	200	500	200	1200	1500
	2nd exit	9000	-	-	-	1500	-
DRJ (NM)	In Nautical Miles	745	1233	755	-	2218	-
IM	Naval Base + City Structure	4	3	1	2	2	2
SS	Douglas Sea State Scale	2	2	5	1	1	1

3 Background

In this section, the SAPEVO-M and VIKOR methods will be described, which will be used in hybrid modeling as tools to support decision-making.

3.1 SAPEVO-M method

In general, the desired result in a given Multicriteria Decision Support problem can be identified among four types of reference problems [13]:

I - Problematic P.α - aims to clarify the decision by choosing a subset of alternatives as restricted as possible. Therefore, the desired result is a choice;

II - Problematic P.β - aims to clarify the decision by a screening resulting from the allocation of each alternative to a class (or category). Therefore, the desired result is a sort action;

III - Problematic P.γ - aims to clarify the decision by an organization obtained by the regrouping of part or all actions in equivalence classes, which are ordered partially or completely, according to the preferences of the decision-maker(s). Therefore, the desired result is a sort or ranking procedure;

IV - Problematic P.δ - aims to clarify the decision by a description of the actions and their consequences. Therefore, the desired result is a cognitive procedure or a description.

The Simple Aggregation of Preferences Expressed by Ordinal Vectors - Multi Decision Makers method (SAPEVO-M) represents a new version of the SAPEVO ordinal method [14], especially for problems of the P.γ type. This evolution of the original version extended the use of the method to multiple decision-makers [15].

The SAPEVO method unfolds the decision-making problem from three basic steps [15], which are:

1. Transforms the ordinal preferences of the criteria into a vector of criterion weights;
2. Transforms the ordinal preferences of alternatives for a given set of classification criteria into partial weights of alternatives; and
3. Determines the global weights of the alternatives.

The method has been applied in several areas, such as the selection of equipment for a bakery [16] and the selection of a troop landing ship for the Argentine navy [17].

SapevoWeb Computer System. The SapevoWeb system was developed from a partnership between the technical staff of the Naval Systems Analysis Centre (CASNAV), a research group of the Graduate Program in Production Engineering of the Fluminense Federal University (UFF) and a research group of the Graduate Program in Systems and Computer Engineering of the Military Institute of Engineering (IME) [15].

SapevoWeb code was developed in python language, using the Django framework, and HTML [18]. The program allows the inclusion of a sufficiently large integer of decision-makers, criteria and alternatives, limited only by the processing capacity of the server. The computational tool can be accessed at www.sapevoweb.com [15].

3.2 VIKOR method

The *ViseKriterijumska Optimizacija i Kompromisno Resenje* (VIKOR) method was developed as a method of commitment programming, to determine a ranking with weights of a set of alternatives [19]. To observe this weight that measures the ranking, a few steps must be followed [20,21] such as:

Step 1: Determine the highest values f_i^* and the lowest values f_i^- of all the alternatives in each criterion, i = 1, 2, ..., n.

$$f_i^* = max_j f_{ij}$$
$$f_i^- = min_j f_{ij}$$

Where f_i^* is the highest value presented by the alternatives in each criterion;
f_i^- is the lowest value presented by the alternatives in each criterion; and
f_{ij} is the value of the alternative in a given criterion.

Step 2: Calculate the values S (maximum utility group) (1) and R (minimum individual weight) (2), with j = 1, 2, ..., j, in the relationships; where W_i is the weight of the criteria.

$$S_j = \frac{\sum_{i=1}^{n} W_i(f_i^* - f_i^-)}{(f_i^* - f_i^-)} \quad (1)$$

$$R_j = max_j \left(\frac{\sum_{i=1}^{n} W_i(f_i^* - f_i^-)}{(f_i^* - f_i^-)} \right) \quad (2)$$

S_j: maximum utility group of the alternative j;
W_i: weights of the criteria obtained by calculating entropy;
R_j: the minimum individual weight of alternative j.

Step 3: Calculate the values of Q_j (3), with j = 1, 2, ..., j, by the ratio in which $S^* = min_j Sj$; $S^- = max_j S_j$ and $R^* = min_j R_j$; $R^- = max_j R_j$. Parameter v is entered as a strategy weight, commonly used as v = 0.5.

$$Q_j = \frac{v(S_j - S^*)}{(S^- - S^*)} + \frac{(1 - V)(R_j - R^*)}{(R^- - R^*)} \quad (3)$$

Where v = 0.5 and Q_j is the final score of an alternative j;

Step 4: Classify the alternatives in a decreasing ordination, using the values obtained by S, R and Q. The results are three classification lists. However, only the values obtained by Q can be considered.

Step 5: Once the Ranking on the decreasing values of Q_i is established, the analysis on the verifications of stability conditions C_1 and C_2, which are obtained through (4) and (5):

C_1 - Acceptable difference/advantage:

$$Q(A_2) - Q(A_1) \geq DQ \quad (4)$$

Where $DQ = \frac{1}{j-1}$ and j is the number of alternatives.

C_2 - Acceptable stability in decision-making: A_1 should be the best rated in S and/or R.

If one of the conditions (C_1 and C_2) is not met, then a cluster of compromise solutions is proposed, which consists of:

Alternatives A_1 and A_2, if only C_2 is not satisfied; or

Alternatives A_1, A_2, ... A_M, if only condition C_1 is not satisfied; The M value is determined for the maximum value of M that satisfies the equation (5):

$$Q(A_M) - Q(A_1) < DQ \tag{5}$$

4 Application of SAPEVO-M and VIKOR methods

First, the SAPEVO-M method will be applied to obtain the weights of the criteria, through the Software SapevoWeb [18]. After this, using the VIKOR method, through the Vikor software [22], the classification of cities will be obtained and stability conditions checked.

4.1 Evaluation of criteria

Three Navy officers with more than 20 years of experience have already been invited to evaluate the criteria that compose the problem. After registering the decision-makers (DM), criteria and alternatives of the cities, the DM will evaluate, one by one, the importance of the criteria and alternatives [15].

After evaluating the criteria chosen by the Navy Officers, the weights of the criteria are obtained, according to Table 2.

Table 2. Weights of the criteria, obtained by applying the SAPEVO-M method.

Criterion	Weight
DS	1,4185
EW	2,9473
DRJ	1,4135
IM	2,6040
SS	0,0131

Analyzing the weights of the criteria, it is observed that the exit width was the criterion that obtained the greatest weight in the evaluation, followed by the infrastructure for maintenance. The state of the sea was considered the least important by the DM.

The SAPEVO-M method allows to know how much an alternative and /or criterion was better ordered, in relation to another, passing additional information to the DM [15]. In other words, this means that the exit width criterion (Weight 2.9473) was

considered about 2 times better or more important than the distance from RJ by sea and distance to the sea.

4.2 Application of the VIKOR method

From the decision matrix demonstrated in Table 3 and including the weight vector (Table 3), acquired by SAPEVO-M, it is necessary to determine the best value f_i^* and the worst value f_i^- of each criterion:

Table 3. Decision matrix of the criteria with their respective weights and the values of f_i^* and f_i^-.

Weights	1,4185	2,9473	1,4135	2,6040	0,0131
	DS	EW	DRJ	IM	S
Salvador/BA	27	450	745	4	2
Natal/RN	5,5	200	1233	3	2
Rio Grande/RS	18	500	755	1	5
Ladário/MS	10000	200	0	2	1
Bethlehem/PA	100	1200	2218	2	1
Manaus/AM	10000	1500	0	2	1
fi*	5,5	1500	2218	4	1
fi-	10000	200	745	1	5

It is worth note the differentiation between the cost criteria (the lower, the better) - Distance to the sea and state of the sea - and benefit (the bigger, the better) - Exit Width, Infrastructure for Maintenance and distance from RJ by sea.

4.3 Obtaining S_i and R_i

After applying (1) and (2), Table 4 is obtained.

Table 4. Standard decision matrix and obtaining S_i and R_i.

	DS	EW	DRJ	IM	SS	S_i	R_i
Salvador/BA	0,0031	2,3805	0,9387	0,0000	0,0033	3,3256	2,3805
Natal/RN	0,0000	2,9473	0,6373	0,8680	0,0033	4,4559	2,9473
Rio Grande/RS	0,0018	2,2672	0,9323	2,6040	0,0131	5,8184	2,6040
Ladário/MS	1,4185	2,9473	1,4135	1,7360	0,0000	7,5153	2,9473
Bethlehem/PA	0,0134	0,6801	0,0000	1,7360	0,0000	2,4295	1,7360
Manaus/AM	1,4185	0,0000	1,4135	1,7360	0,0000	4,568	1,7360

Source: Authors (2020).

It is observed that the city of Ladário obtained the highest value of S_i, while Belém presented the lowest value in this parameter. In relation to the parameter R_i,, it is observed that Belém and Manaus obtained the lowest values, while Rio Grande and Natal presented the highest scores.

4.4 Calculating Q_i and ordering alternatives

Applying (3), Table 5 is obtained.

Table 5. Obtaining Q_i.

	S_i	R_i	Q_i
Salvador/BA	3,3256	2,3805	0,3541
Natal/RN	4,4559	2,9473	0,6992
Rio Grande/RS	5,8184	2,6040	0,6915
Ladário/MS	7,5153	2,9473	1,0000
Bethlehem/PA	2,4295	1,7360	0,0000
Manaus/AM	4,568	1,7360	0,2102
S*, R*	2,4295	1,7360	
S^- , R^-	7,5153	2,9473	

From the data obtained, the decreasing ordering is made, by S, R and Q values. For this, the results compose three classification lists, but only the Q values can be considered (Table 6).

Table 6. Ordering of alternatives.

	S_i	R_i	Q_i	Ranking
Salvador/BA	3,3256	2,3805	0,3541	3
Natal/RN	4,4559	2,9473	0,6992	5
Rio Grande/RS	5,8184	2,6040	0,6915	4
Ladário/MS	7,5153	2,9473	1,0000	6
Bethlehem/PA	2,4295	1,7360	0,0000	1
Manaus/AM	4,568	1,7360	0,2102	2

Analyzing the classification of the cities, it is observed that the best evaluated by the methods was the city of Belém/PA, which obtained the lowest Q value.

4.5 Analysis of results

After establishing the classification of alternatives, the stability conditions should be checked. First analyzing condition C_1 - Acceptable difference/advantage - applying (4), DQ equal to 0.2 is obtained. The difference between the second-placed (Manaus) and the first (Belém) must be greater than or equal to DQ for this condition to be met:

$Q(A_2) - Q(A_1) = 0.2102 - 0.0000 = 0.2102.$

Therefore, Condition C_1 is satisfied, since $0.2102 \geq 0.2$.

For condition C_2, it should be verified if the best-classified alternative also presents the best indices for R and/or S. It is observed that Belém, besides being the best alternative analyzing Q, presents the lowest values in R and S, also satisfying the stability condition C_2. As the two conditions were met, Belém can be considered as the most suitable city to be the headquarters of the Second Brazilian Squadron.

Analyzing Table which presents the normalized values of the alternatives in each criterion, it is observed that the first two placed in the proposed analysis (Belém and Manaus) present the best performance (note 0) in two criteria, which justifies their best classifications rather than the others.

The city of Manaus presents the best score in the criterion with greater weight (exit width) but obtained the worst performance in the distance to the sea and distance from RJ by sea. On the other hand, the city of Belém obtained the second score in the analysis of the exit width and the best performance in the criteria state of the sea and distance from RJ by sea, besides presenting regularity in the other criteria, which corroborates with its choice.

5 Conclusion

The application of the SAPEVO-M method considered the evaluation of three different specialists and made it possible to obtain the values of the weights of the criteria taking into account the opinion of each of them, making the analysis more robust and reliable. Considering that the objective of the article is to select a headquarters for the Second Squadron, the method proved to be quite efficient, since the criteria that obtained the highest weights are of high importance for fulfilling the mission of the city to be chosen as the headquarter.

Regarding the application of the VIKOR method, it was observed that the results obtained presented a consistent basis, with easily verifiable logical chaining, since the cities with the best classifications presented the best performances in the most important criteria. Besides, the verification of acceptable advantage and stability conditions have analyzed results more reliable and safer, providing the decision-making person with extremely relevant information for the decision.

Given the above, it was clear that the hybrid modeling using SAPEVO-M and VIKOR methods can be used to solve complex problems of the most varied types, thus being a combination of methods of great utility for the contribution of decision making, considering that it takes into account the evaluation of several criteria made by multiple decision-makers, besides allowing a rich and robust analysis of the results obtained, which makes the decision-making process more transparent.

It is also emphasized that, because there are web softwares available, including free of charge, the application of the methods were greatly facilitated, since their axiomatics involve calculations often complex and long, which implements a software, which facilitates the use of methods, a determining factor for the diffusion of this modeling.

Finally, the future papers could address comparative analyses between cities where there are no pre-structured bases, including other criteria such as ease of access to coast and area available for the construction of a naval complex.

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Localización de proveedores de salud en zonas rurales en países en desarrollo: Un enfoque de programación lineal entera mixta

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Resumen. Este trabajo analiza políticas públicas relacionadas con el cubrimiento de las instalaciones de salud en el área rural de Colombia. La localización, la cobertura y el tipo de instalación de salud en muchos países emergentes no han sido factores a tener en cuenta cuando se ha diseñado la red hospitalaria. Esto ha generado que muchas regiones experimenten una baja cobertura y otras estén sobrecubiertas. En el caso de Colombia, la jerarquía de niveles de servicio de las instalaciones de salud ha generado que el área rural cuente con deficiencias en el cubrimiento espacial al tener acceso solamente a servicios primarios. Por esta razón, este trabajo evalúa la situación actual en términos de la cobertura espacial de las instalaciones de salud y propone un modelo matemático de programación lineal entera mixta (MILP) para incrementar esta cobertura, así como la de la demanda teniendo en cuenta restricciones particulares de la situación rural de Colombia. Los resultados evidencian como el cambio en la distribución geográfica de las instalaciones existentes puede mejorar la cobertura espacial al reducir las distancias que los habitantes de una vereda deben recorrer para atender las necesidades de los servicios médicos.

Palabras claves: Localización instalaciones de salud, problema de localización de instalaciones, proveedores de salud, logística hospitalaria.

1 Introducción

El acceso a los servicios de la salud está definido por diferentes factores tales como disponibilidad de la oferta, acceso físico, efectividad del servicio, barreras de utilización, etc. [1]. El bajo acceso es una de las principales causas por las que no se previenen enfermedades y las personas terminan sufriendo grandes daños en su salud [2]. El problema se incrementa en países de medio y bajos ingresos (países en desarrollo o emergentes) donde se mantienen grandes brechas en la prestación de la salud en comparación a países desarrollados en servicios como, por ejemplo, la asistencia a la infancia y la maternidad [3].

De acuerdo a Penchansky et al. [4] la accesibilidad a la salud tiene 5 dimensiones, de las cuales las dos primeras, accesibilidad y disponibilidad, hacen referencia al acceso espacial, mientras que las tres restantes tienen que ver con factores socio-económicos. Para garantizar ese acceso espacial, la planeación estratégica de la red hospitalaria es parte fundamental para minimizar costos gubernamentales y maximizar el bienestar de la población [5]. Sin embargo, el diseño de esta red es un problema que comprende múltiples restricciones según el caso específico que se esté estudiando.

Para Colombia, como en muchos países en vía de desarrollo, la cobertura de los servicios de salud, hasta el alcance de nuestra investigación, tiene pocos indicadores como por ejemplo el número de camas por cada 1000 habitantes [6]. El área rural es la que presenta mayores dificultades; dado que, allí predominan los "puestos de salud", instalaciones pequeñas que solo prestan servicios primarios; hay insuficientes "centros de salud", instalaciones secundarias que ofrecen un mayor nivel de atención; y escasos hospitales, que pueden ser de complejidad 1C, la instalación más básica, hasta 3H el más alto nivel de salas de cirugía, de cuidados intensivos, etc. Además, el servicio funciona jerárquicamente, es decir cuando un paciente en el área rural requiere atención médica pasa primero por un puesto de salud y ahí, es reasignado a un centro de salud y luego del centro de salud a un hospital [7].

Uno de los enfoques con los que se ha tratado el problema de diseño de redes hospitalarias a nivel mundial ha sido el problema de localización de instalaciones [8]. Este es un modelo de optimización ampliamente utilizado en investigación de operaciones, al cual le han dado múltiples perspectivas para mejorar la cobertura de este servicio [9]. Sin embargo, Ahmadi et al. [9] y Peng et al. [10] han identificado aún muchos retos para estudiar como la ubicación de instalación según el tipo, según el grado de complejidad y teniendo en cuenta las dificultades de la zona rural en países en vía de desarrollo.

Por todo lo anterior, este artículo inicialmente evalúa la situación actual del área de estudio en términos de cobertura espacial y de la demanda. Con esto, se propone una formulación MILP con el objetivo de maximizar la cobertura con el actual número y el mismo tipo de instalaciones teniendo en cuenta las restricciones particulares de este caso de estudio. El área utilizada para el estudio es la región del Tequendama. Está cerca de Bogotá, la capital de Colombia. Es un área rural en el departamento de Cundinamarca que cuenta con aproximadamente 140.800 habitantes.

Este artículo está organizado como se explica a continuación. La sección 2 muestra los antecedentes de este trabajo y una breve revisión de los conceptos requeridos para el desarrollo del trabajo. La sección 3 presenta la definición formal del problema y el modelo matemático asociado. La sección 4 describe el caso de estudio de la región del Tequendama y el uso del modelo propuesto. La sección 5 presenta los resultados principales de la implementación en el caso de estudio. Finalmente, la sección 6 discute las conclusiones de este trabajo y sugiere algunos trabajos futuros.

2 Antecedentes

La localización de instalaciones de salud ha sido un tema ampliamente estudiado. Ahmadi et al. [9] presentaron un resumen de todos los modelos que se han utilizado

para este fin. Ellos encontraron que las investigaciones predominantes han sido con modelos de cobertura, dado el interés por la accesibilidad geográfica al servicio de salud [2], [8]. De hecho, el más usado es el modelo de localización de máxima cobertura (MCLP, por sus siglas en inglés), dado que trata con el problema de cubrir las necesidades de salud de los pacientes teniendo un número limitado de instalaciones [10]. Este modelo ha sido estudiado por autores como Ye et al. [11] quienes combinaron el modelo con un sistema de información geográfico (GIS) para evaluar la accesibilidad a la salud y para apoyar decisiones de localización. Otro ejemplo es Dzatora et al. [12] quienes comparan el modelo p-medianas con el MCLP encontrando que este último depende de los radios de cobertura que se definan previamente. Su caso de estudio fue Mackay en Queensland, Australia.

Sin embargo, la mayoría de esos estudios se han centrado en casos de países desarrollados, como los ejemplos antes mencionados. Esto implica que la accesibilidad espacial considera características diferentes en comparación a los países en desarrollo; dado que, los primeros tienen mayor presupuesto y mejor infraestructura [13]. De los estudios que se han encontrado en países en vía de desarrollo se destacan Doerner et al. [14] quienes ubican instalaciones de salud móviles para incrementar la atención de servicios de salud primarios. Ellos resaltaron que la distancia es un factor fundamental para el cubrimiento de los servicios de salud en zonas rurales. Por otro lado, Pu et al.[2] implementaron un MCLP para mejorar la accesibilidad espacial en North Kivu, República Democrática del Congo. Ellos enfatizan que el cubrimiento espacial más bajo se da en zonas rurales por las dificultades para transportarse por la falta de vías. También hay otros estudios que analizan el cubrimiento espacial en países en desarrollo con la implementación de GIS sin uso de modelos matemáticos [15], [16].

Todos los anteriores estudios llegan a la conclusión de que el área rural es la zona crítica para mejorar la cobertura en servicios de salud en países en desarrollo; sin embargo, pocas veces se usan herramientas formarles para la toma de decisiones en estos países [17]. Adicionalmente, tanto Ahmadi et al. [9] como Hamid [10] mencionan la importancia de tomar en cuenta las restricciones asociadas al tipo de instalación de salud que se está localizando, los diferentes tipos de servicios que presta cada tipo de instalación, así como la optimización de instalaciones ya existentes. Estos vacíos en la literatura son las razones que motivaron la investigación de este artículo.

3 Propuesta

Como se mencionó anteriormente, el estudio se desarrolló considerando la falta de literatura asociada a las restricciones de los diferentes tipos de instalaciones de salud, los distintos tipos de servicios y la redistribución de instalaciones ya existentes. Estas restricciones han sido resaltadas como retos y futuras investigaciones en trabajos previos [9], [10]. El interés en la zona rural es dado los problemas que han encontrado anteriores estudios en la falta de accesibilidad que estas zonas tienen a los servicios de salud por factores de distancia y dificultad en el transporte [2], [14]. El caso de estudio colombiano se selecciona al tener estas características particulares que representan un reto; puesto que, la red hospitalaria se compone de distintos tipos de instalaciones que

prestan servicios según su grado de complejidad. Además, es una zona con más del 98% de área rural [18] en un país en desarrollo, presentando los problemas de accesibilidad geográfica antes mencionados que disminuyen la calidad de prestación de servicios de salud. La sección 4 muestra a profundidad las particularidades del caso de estudio seleccionado.

Considerando las razones por las que se desarrolló este estudio, en esta sección se presenta en primer lugar la definición formal del problema de localización de instalaciones de salud y, en segundo lugar, se muestra el modelo matemático de programación lineal entera mixta (MILP, por sus siglas en inglés) asociado a este problema.

3.1 Localización de instalaciones de proveedores de servicios de salud modelo MILP

La definición del problema se detalla a continuación:

Se consideraron en un área rural un conjunto de clientes (hogares) $H = \{1...j\}$ geográficamente distribuidos según la densidad residencial. Cada hogar $j \in H$ tenía una demanda d_{sj} de unos servicios de salud $S = \{1...s\}$ que debía ser satisfecha por algún tipo de instalación de salud $F = \{1...k\}$ de algún grado de complejidad $N = \{1...n\}$ localizada en alguna ubicación $I = \{1...i\}$. La capacidad de cada tipo de instalación $k \in F$ tuvo un límite dado por el parámetro cap_{kns} según el grado de complejidad $n \in N$ para cada servicio $s \in S$. Consideramos que cada instalación de salud ubicada en $i \in I$ tenía un radio de cobertura con respecto a cada hogar $j \in H$ dado por el parámetro a_{ijl} que es calificado según los niveles de cobertura $L = \{1...l\}$ por el parámetro γ_l en el cual $\gamma_1 > \gamma_2 > \cdots > \gamma_L$. Adicionalmente, se supuso una calificación β_{kn} de los servicios de salud prestados por un tipo de instalación $k \in F$ según el grado de complejidad $n \in N$. Finalmente, tuvimos en cuenta un número máximo N_{kn} de instalaciones tipo $k \in F$ en el grado de complejidad $n \in N$ que podía habilitarse para prestar los servicios de salud y un mínimo porcentaje α de la demanda de cada servicio a cubrir.

3.2 Formulación del modelo

La siguiente notación es usada para formular el modelo de FLP:

Conjuntos

H conjunto de hogares; $j \in H$
I conjunto de potenciales localizaciones para instalaciones médicas; $i \in I$
F conjunto de tipo de instalación de salud; $k \in F$
L conjunto de niveles de cobertura de las instalaciones de salud; $l \in L$
N conjunto de grados de niveles de complejidad de las instalaciones de salud; $n \in N$
S conjunto de servicios de salud; $s \in S$

Parámetros

d_{sj} demanda esperada del servicio s del hogar j
Q_{kns} máxima capacidad habilitada para cada tipo de instalación k en el grado de complejidad n en el servicio s

a_{ijl} parámetro binario donde es 1 si la instalación de salud i cubre al hogar j en el nivel de cobertura l y 0 en otro caso
β_{kn} calificación dada al tipo de instalación k según el grado de complejidad n
N_{kn} número máximo de instalaciones tipo k en el grado de complejidad n que pueden habilitarse
α porcentaje mínimo de la demanda a cubrir para cada servicio
γ_l calificación del nivel de cobertura l
M número muy grande para restricciones lógicas

Variables de decisión

$X_{ikn} = \begin{cases} 1 \text{ Si se abre una intalación de salud tipo } k \text{ en } i \text{ del grado de complejidad } n \\ 0 \quad \text{En otro caso} \end{cases}$

$Z_{jl} = \begin{cases} 1 \text{ Si el hogar } j \text{ está cubierto en el nivel de cobertura } l \\ 0 \quad \text{En otro caso} \end{cases}$

Y_{sjkni} = Proporción de la demanda del servicio *s* del hogar *j* cubierto por la instalación de salud tipo k en el grado de complejidad *n* localizada en i

La formulación es como sigue:

$$Max \sum_{j\in H}\sum_{i\in I}\sum_{k\in F}\sum_{l\in L}\sum_{n\in N}\sum_{s\in S}\beta_{kn}\gamma_l a_{ijl} d_{sj} Y_{sjkni} \quad (1)$$

Sujeto a:

$$\sum_{i\in I}\sum_{n\in N}\sum_{k\in F} a_{ijl} X_{ikn} \geq Z_{jl} \quad \forall j,l \; ; \; j \in H, l \in L \quad (2)$$

$$\sum_{i\in I}\sum_{n\in N}\sum_{k\in F} a_{ijl} X_{ikn} \leq M Z_{jl} \quad \forall j,l \; ; \; j \in H, l \in L \quad (3)$$

$$\sum_{i\in I}\sum_{n\in N}\sum_{k\in F} Y_{sjkni} \leq 1 \quad \forall j,s \; ; \; j \in H, s \in S \quad (4)$$

$$\sum_{j\in H}\sum_{i\in I}\sum_{k\in F}\sum_{n\in N} d_{sj} Y_{sjkni} \geq \alpha \sum_{j} d_{sj} \quad \forall s \; ; \; s \in S \quad (5)$$

$$\sum_{k\in F}\sum_{n\in N} X_{ikn} \leq 1 \quad \forall i \; ; i \in I \quad (6)$$

$$\sum_{j\in H} d_{sj} Y_{sjkni} \leq Q_{kns} X_{ikn} \quad \forall i,s,n,k \; ; \; i \in I; s \in S; n \in N; k \in F \quad (7)$$

$$\sum_{i\in I} X_{ikn} = N_{kn} \quad \forall k,n \; ; k \in F; n \in N \quad (8)$$

$$Y_{sjkni} \geq 0 \quad \forall i,s,n,k,j \; ; \; i \in I; s \in S; n \in N; k \in F; j \in H \quad (9)$$

$$X_{ikn}, Z_{jl} \in \{0,1\} \; \forall i,k,n,j,l \; ; i \in I; k \in F; n \in N; j \in H; l \in L \quad (10)$$

La función objetivo (1) maximiza la calidad de la cobertura de la demanda de salud. El conjunto de restricciones (2) y (3) establece si un hogar está cubierto en algún nivel de cobertura si este está dentro del rango de una instalación. El conjunto de restricciones

(4) asegura que la demanda de cada servicio de un hogar no se puede cubrir en más del 100%. El conjunto de restricciones (5) asegura que la proporción cubierta de la demanda de cada servicio de salud es mayor o igual que un porcentaje fijado previamente. El conjunto de restricciones (6) evita que en una misma localización se habilite más de un tipo de instalación. El conjunto de restricciones (7) garantiza que la demanda de cada servicio cubierta por una instalación no es mayor que su capacidad habilita para ese servicio. El conjunto de restricciones (8) limita el número de instalaciones de cada tipo en cada grado de complejidad que se pueden habilitar. Finalmente, el conjunto de restricciones (9) y (10) hacen referencia a la naturaleza de las variables de decisión de no-negatividad y binarias.

4 Descripción del caso de estudio

Colombia cuenta con una división política constituida por departamentos, que a su vez se dividen en municipios agrupados en provincias. Este estudio se enfoca en la provincia del Tequendama, localizada al sur occidente del departamento de Cundinamarca, conformada por 10 municipios: Anapoima, Anolaima, Apulo, Cachipay, El Colegio, Quipile, San Antonio del Tequendama, Tena, Viotá y La Mesa (lugar con mayor población). La población total es de aproximadamente 140.800 habitantes. El 98,9% es área rural y comprende aproximadamente 300 veredas [18]. Una vereda es una subdivisión administrativa de cada municipio en Colombia.

En la provincia existen actualmente 5 hospitales, 4 centros de salud y 21 puestos de salud que se clasifican por los grados de complejidad mostrados en la Tabla 1. Los puestos de salud tienen el nivel de complejidad más bajo prestando solamente servicios básicos de consulta externa y odontología. En el caso de los centros de salud, estos tienen dos tipos de grados de complejidad que se diferencian en que el grado 2B presta servicios de atención a partos adicional a los servicios que se prestan en el grado 1B.

Tabla 1. Clasificación y cantidad de instituciones actuales en la provincia del Tequendama. Fuente: (Vargas, Gomez, & Amaris, 2014)

Tipo de instalación	Grado de complejidad	Cantidad	Servicios								
			1	2	3	4	5	6	7	8	9
Puesto de salud	1A	21			X	X				X	
Centro de salud	1B	3	X	X	X	X	X			X	
	2B	1	X	X	X	X	X	X	X	X	
Hospital	1C	1	X	X	X	X	X	X	X	X	X
	2C	2	X	X	X	X	X	X	X	X	X
	3C	1	X	X	X	X	X	X	X	X	X
	3H	1	X	X	X	X	X	X	X	X	X

1=Hospitalización, 2=Observación, 3=Medicina general, 4=Consulta especializada, 5=Servicio de urgencias, 6=Obstetricia, 7=Atención de partos, 8=Odontología, 9=Cirugía general.

Por último, los hospitales prestan todos los tipos de servicio; sin embargo, según el grado de complejidad varía la capacidad de la instalación [19]. Los servicios con mayor

demanda son la consulta médica general (64% de la atención en las instituciones), la odontología (12%) y la consulta médica especializada un 8% [20]. La distribución geográfica de las instalaciones se muestra en la Fig. 1. Cabe resaltar que la institución de mayor nivel, actualmente, es el Hospital de La Mesa (localización verde 15). Sin embargo, los pacientes con enfermedades o urgencias de mayor complejidad deben ser remitidos a los Hospitales de Soacha (municipio al sur de Bogotá) o Bogotá que cuentan con mayor grado. El tiempo promedio de viaje desde la provincia hacia Bogotá es de 2 horas [21].

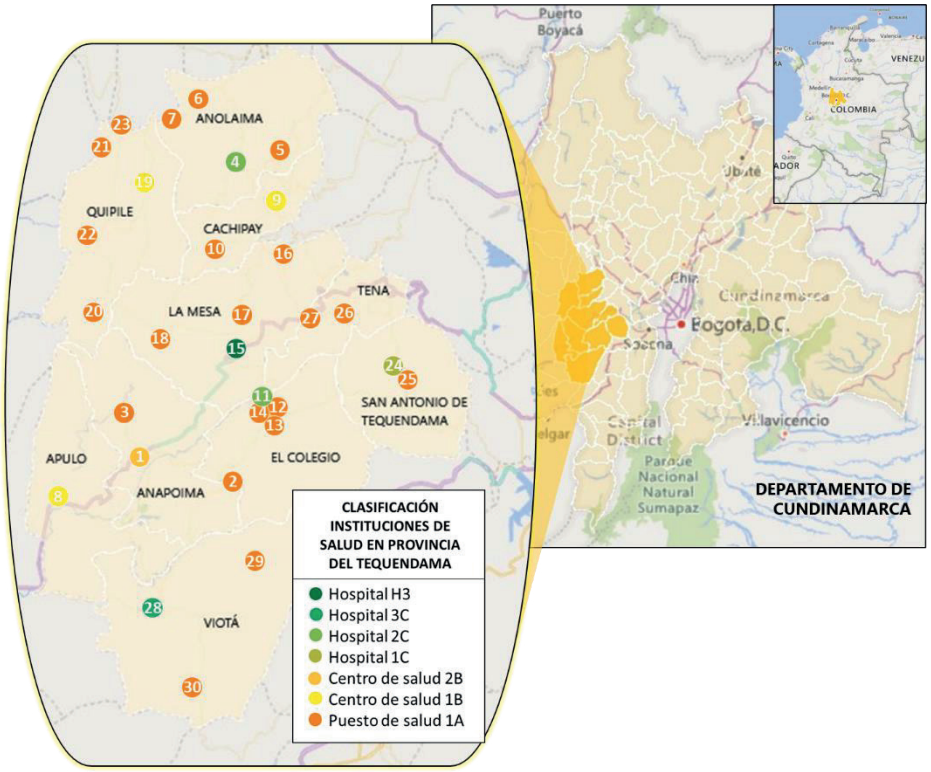


Fig. 1. Distribución geoespacial de las instalaciones de salud en la provincia del Tequendama

Actualmente, las estadísticas presentan que la capacidad instalada de las instituciones en la salud en Colombia es baja, debido a que solo hay 1,7 camas por cada 1000 habitantes, lo cual no alcanza a cumplir los estándares de la Organización Mundial de la Salud, que indica que esta razón debe estar entre 2,5 y 4 camas para poblaciones mayores a los 100.000 habitantes [21]. En Cundinamarca este indicador es de 1,04 por mil habitantes. Adicional a esto, la dispersión de la población rural ascendió en promedio a 64.6% en la provincia del Tequendama, solo el 13% de la red vial de la región se encuentra pavimentada y el 40% de esa malla vial se encuentra en mal estado, lo cual incrementa el tiempo que se necesita para llegar a la instalación más cercana. Otro factor que disminuye la calidad de la salud es la pobreza, en el Tequendama el indicador

de personas sin aseguramiento a la salud es de aproximadamente 11,1% en lo urbano y en lo rural 10,7%, por lo cual las tasas de mortalidad ascienden en las comunidades de mayor pobreza [21].

4.1 Recolección y preparación de datos

Para este estudio solo se tuvieron en cuenta las instituciones públicas; debido a que, estas aseguran cobertura médica a la totalidad de los habitantes de la región, mientras que las instituciones privadas solo ofrecen los servicios a una población parcial. Los puntos de demanda se agregaron por veredas usando un punto central para su ubicación. Para la distribución de la población por vereda se utilizó la distancia al casco urbano principal de cada municipio, usando una clasificación de 3 radios, asignando 50% de la población al primer radio (más cercano al casco urbano), 30% al siguiente y 20% al último (más alejado del casco urbano).

Todas las ubicaciones fueron establecidas por Google Maps™. La distancia fue calculada con la ecuación de Haversine [22]. Para considerar la estructura vial y otras condiciones geográficas se usó un factor multiplicador de 1.8 [23]. Los radios de cubrimiento para cada nivel de cobertura fueron estimados según el tipo de institución y el nivel de complejidad usando una función escalonada de 4 niveles similar a la empleada por Balcik et al. [24] con un máximo radio de 14 kilómetros para el hospital con grado 3H y un máximo radio de 5 kilómetros para el puesto de salud grado 1A.

Por otro lado, para el cálculo de la oferta y la demanda, se clasificaron los servicios prestados según los indicadores de salud [25], [26], [27] por cada tipo de instalación según el grado de complejidad. Estos se relacionaron con la capacidad instalada en cada instalación. La capacidad para cada servicio se obtuvo, en el caso las mesas de parto, las salas de quirófanos y las camas de hospitalización, según la distribución colombiana departamental [21],[25],[27],[28] haciendo una relación con la proporción de población de la vereda respecto al departamento. Para las camillas de observación [29], se usó una relación porcentual de información verificada de camas y camillas de los municipios de Anolaima [12], [30], [31], El Colegio , La Mesa [32], San Antonio del Tequendama [33] y Viotá [32]. La información restante se calculó con consultas directas a la administración del Hospital de la Mesa y el Hospital del Colegio. En coherencia, se asumió que todos los puestos de salud tienen un comportamiento idéntico[34].

Por otro lado, la demanda se extrajo de los indicadores anuales reportados por REPS de servicios atendidos en el departamento [35]. Para la distribución de la demanda en todos los tipos de instalaciones, se creó un porcentaje de cobertura por municipio que tenía en cuenta el número y tipo de entidades en cada uno, sin que los puestos de salud cubrieran más del 25% y que los hospitales y centros de salud cubrieran más del 50% de la demanda total por municipio. Seguido a esto, la distribución de la demanda por veredas se expandió geográficamente a cada una teniendo en cuenta el porcentaje de población que reside en ellas y su peso respecto al total de habitantes de cada municipio; no obstante, fue necesario realizar una variación de esta distribución geográfica, debido a que al recopilar los datos, se observó que los servicios como obstetricia, atención a partos y cirugías, son poco demandados y al asignarlos de esta forma, se obtenía una menor cantidad a la real, caso opuesto si se aproximaba al mayor puesto que el

comportamiento se convertía en uniforme y las cifras se desbordaban exageradamente. Por consiguiente, se usaron tres tipos de distribuciones geográficas de la demanda (DGD1, DGD2 y DGD3) donde cada una tiene una asignación aleatoria por vereda de los servicios mencionados con el fin de garantizar la exactitud de los datos y comparar su efecto frente a la solución del modelo matemático.

5 Resultados

El modelo matemático fue implementado en el software GAMS. Se probaron diferentes instancias variando el tipo de distribución geográfica de la demanda (DGD) y el porcentaje mínimo a cubrir de esta α.

En la Tabla 2 se muestran los resultados de la demanda cubierta. Observamos que para los servicios de cirugía y de hospitalización no se alcanza a cubrir más del 30% de la demanda. Esto es debido a las capacidades de ambos servicios a nivel general en la provincia, la cual no es suficiente para la demanda sin importar el tipo de DGD, evidenciando una deficiencia que afecta la rápida respuesta que se puede necesitar para estos servicios. A nivel del modelo matemático, esto ocasiona que la variación del porcentaje mínimo a cubrir α no pueda superar el 30%, dado que de no ser así el modelo pasaría a no tener una solución factible. No obstante, esto no afecta la cobertura de la demanda en los otros servicios contemplados, donde se llega a cubrir hasta el 100% de la demanda. Es decir, que para estos otros servicios el parámetro α no juega un papel importante. A nivel general, el porcentaje de cubrimiento de la demanda total oscila dentro del 97%, porcentaje que es bueno para mejorar el servicio de salud en la zona. Asimismo, se puede concluir que independientemente del caso de demanda, dicho porcentaje en el modelo no se ve afectado por el parámetro α.

Tabla 2. Porcentaje de la demanda cubierta para cada tipo de servicio y a nivel general según la variación del tipo de DGD y el porcentaje mínimo de demanda a cubrir α.

DGD	α	Porcentaje de cubrimiento de la demanda para cada servicio									
		1	2	3	4	5	6	7	8	9	General
DGD1	5%	85.1%	100%	100%	100%	100%	100%	100%	100%	28.8%	97.2%
	10%	85.1%	100%	100%	100%	100%	100%	100%	100%	28.8%	97.2%
	25%	85.1%	100%	100%	100%	100%	100%	100%	100%	28.8%	97.2%
DGD2	5%	84.8%	100%	100%	100%	100%	100%	100%	100%	29%	97.3%
	10%	84.8%	100%	100%	100%	100%	100%	100%	100%	29%	97.3%
	25%	84.8%	100%	100%	100%	100%	100%	100%	100%	29%	97.3%
DGD3	5%	84.8%	100%	100%	100%	100%	100%	100%	100%	29.1%	97.3%
	10%	84.8%	100%	100%	100%	100%	100%	100%	100%	29.1%	97.3%
	25%	84.8%	100%	100%	100%	100%	100%	100%	100%	29.1%	97.3%

1=Hospitalización, 2=Observación, 3=Medicina general, 4=Consulta especializada, 5=Servicio de urgencias, 6=Obstetricia, 7=Atención de partos, 8=Odontología, 9=Cirugía general.

Por otro lado, los resultados mostraron que el cubrimiento espacial con las instituciones reubicadas aumentó con respecto al cubrimiento actual, ya que el porcentaje de población cubierta en nivel de cobertura 1, 2 y 3 obtuvo un incremento en los 3 tipos

de DGD, siendo el mayor el tipo de DGD1 con un aumento del 4.5%, 9.81% y 1.6% respectivamente. En el caso del nivel de cobertura 4 el porcentaje de población en este nivel disminuyó en un 15.35%, lo que indica que las veredas tendrían mayor acceso geográfico al estar más cerca a las instalaciones prestadoras de servicios de salud, es decir que el tiempo de transporte de sus hogares a las instituciones es menor para la atención de sus necesidades médicas. Esto se puede evidenciar en la Fig. 2 que ilustra el porcentaje de población en cada nivel con un α del 5%.

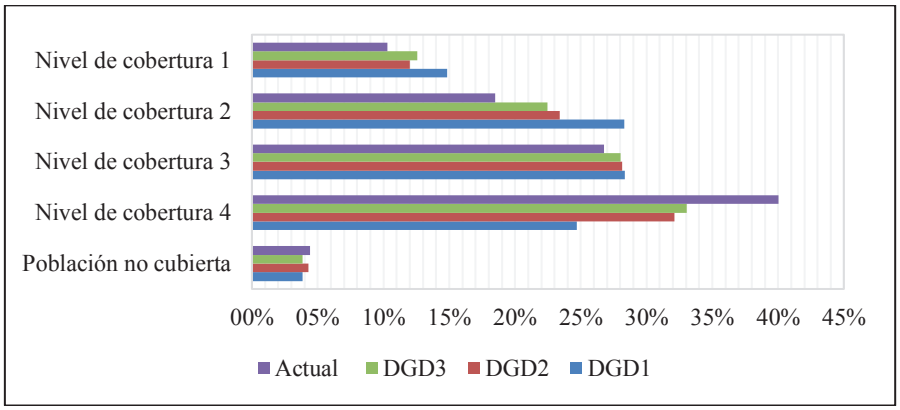


Fig. 2. Porcentaje de cubrimiento en cada nivel de cobertura según cada tipo de DGD vs. La situación actual.

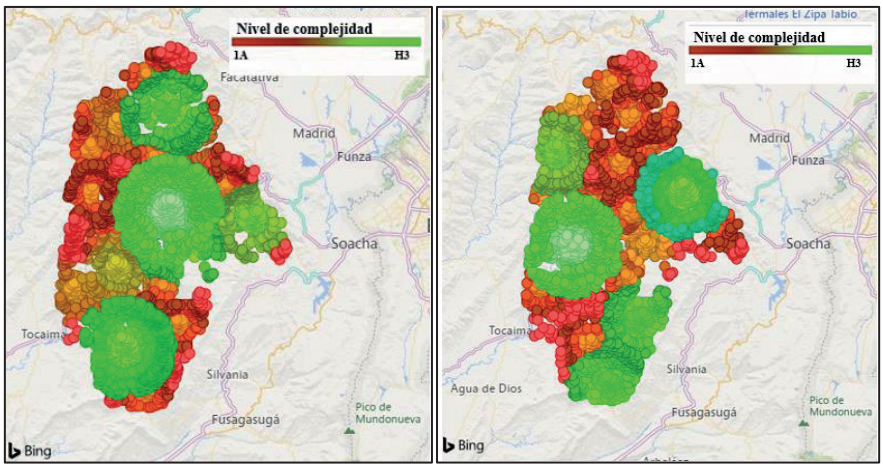
Adicional a esto, los resultados de la asignación de los diferentes tipos de instituciones evidencian cambios importantes. En la Tabla 3 se muestran estos cambios, las ubicaciones que no aparecen es porque se mantuvieron igual que las mostradas en la Fig. 1. De los cambios más significativos son los de los hospitales; dado que, se reubica el de complejidad H3 de La Mesa (localización 15) a Anapoima (localización 3) en un caso o a Quipile (localización 20), el de complejidad 3C de Viotá (localización 28) a Tena (localización 26). Por su parte, los hospitales de complejidad 2C, ubicados en Anolaima (localización 4) y El Colegio (localización 11), se reubican en Viotá (localización 29/30). La ubicación geográfica de cada localización se puede ver en la Fig. 1.

Con estos cambios se puede observar cómo esta nueva configuración (solución DGD1 con α 5%) obtiene una mejor cobertura geográfica considerando que los hospitales tienen un mayor alcance (Ver Fig. 3). Es decir, que reubicarlos tendría una incidencia positiva en el acceso espacial al disminuir las distancias entre los hogares y las instalaciones de salud como se observaba en la Fig. 2. Por otro lado, los centros y puestos de salud se distribuyen a lo largo de los municipios restantes, muchos de ellos no cambian de ubicación. La configuración de este tipo de instalaciones que atienden los servicios más básicos (consulta externa y odontología) logra que se pueda responder de manera efectiva a la demanda considerando que donde se ubican los centros y puestos de salud es donde hay una mayor demanda de estos. La distribución de esta demanda se puede ver en la Fig. 4 donde el área roja en el centro representa las áreas con mayor demanda que geográficamente coincide con las ubicaciones de los centros y puestos de

salud. Esto genera que con estas instituciones se descongestionen los hospitales para que en ellos se concentre la atención de los servicios especializados.

Tabla 3. Cambios de los tipos de instalación asignados a las localizaciones actuales en dos soluciones del modelo

Localización	Municipio	Situación actual	Solución DGD1 - α 5%	Solución DGD3 - α 5%
1	Anapoima	Centro 2B	Puesto 1A	Puesto 1A
3	Anapoima	Puesto 1A	Hospital H3	Puesto 1A
4	Anolaima	Hospital 2C	Puesto 1A	Puesto 1A
6	Anolaima	Puesto 1A	Puesto 1A	Centro 1B
8	Apulo	Centro 1B	Puesto 1A	Hospital 2C
9	Cachipay	Centro 1B	Puesto 1A	Puesto 1A
11	El Colegio	Hospital 2C	Puesto 1A	Centro 1B
14	El Colegio	Puesto 1A	Centro 1B	Puesto 1A
15	La Mesa	Hospital H3	Puesto 1A	Centro 1B
19	Quipile	Centro 1B	Puesto 1A	Puesto 1A
20	Quipile	Puesto 1A	Centro 1B	Hospital H3
22	Quipile	Puesto 1A	Hospital 1C	Centro 2B
23	Quipile	Puesto 1A	Centro 1B	Hospital 1C
24	San Antonio	Hospital 1C	Puesto 1A	Puesto 1A
25	San Antonio	Puesto 1A	Puesto 1A	Hospital 2C
26	Tena	Puesto 1A	Hospital 3C	Puesto 1A
27	Tena	Puesto 1A	Centro 2B	Puesto 1A
28	Viotá	Hospital 3C	Puesto 1A	Puesto 1A
29	Viotá	Puesto 1A	Hospital 2C	Hospital 3C
30	Viotá	Puesto 1A	Hospital 2C	Puesto 1A



A. **B.**

Fig. 3. Mapa de calor del cubrimiento de las instalaciones de salud en A. la situación actual y B. situación propuesta con el parámetro α 5% con el tipo DGD1.

De los resultados, la configuración espacial de la DGD1 con un α de 5% es la que presenta mejores indicadores al tener un mayor porcentaje de cubrimiento de la demanda y una mejor distribución de las instituciones, al cubrir un mayor número de veredas dentro de la región en su primer nivel de cobertura. Esto se puede evidenciar en la Fig. 3 donde los puntos rojos (que son los que no se encuentran en ningún nivel de cobertura) son menores comparado con la situación actual.

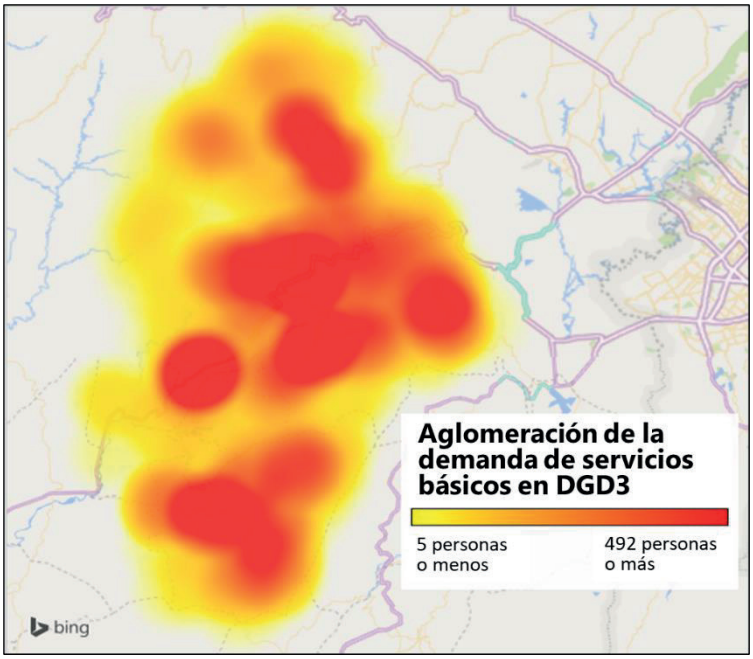


Fig. 4. Mapa de calor de la demanda aglomerada de los servicios básicos de toda la región del Tequendama según la distribución geográfica de la demanda 3 (DGD3). Las unidades de demanda son número de personas que requieren un servicio

6 Conclusiones y trabajos futuros

Esta investigación presenta una propuesta para mejorar la cobertura de los servicios de la salud con una nueva configuración de la red hospitalaria de la provincia del Tequendama. Los resultados obtenidos del modelo satisfacen las demandas de los servicios a nivel general, teniendo en cuenta que en los lugares donde se aglomera la demanda, los servicios más solicitados (servicios básicos) son cubiertos por puestos y centros de salud que se ubicaron en la zona. Esto ayuda a descongestionar los hospitales y facilitarles el cubrimiento de servicios de mayor complejidad por parte de estos últimos. Asimismo, la redistribución propuesta de las instituciones garantizaría que la accesibilidad a los prestadores de salud sea mayor, ya que hasta un 18% más de viviendas quedarían en los primeros dos niveles de cobertura, disminuyendo las distancias de las diferentes veredas a cualquier institución.

Por otro lado, se observa que con las capacidades existentes para cada instalación se puede cubrir más del 90% de la demanda de todos los servicios a excepción de cirugía y hospitalización. Estos dos servicios se resaltan como puntos críticos que obligan a los habitantes de la provincia del Tequendama a trasladarse por mínimo 2 horas de viaje a cubrir la demanda de alguno de estos servicios en municipios o ciudades cercanas, como Soacha y Bogotá, que puedan atender las deficiencias que hay en su zona al contar con hospitales de mayores grados de complejidad. A nivel del modelo matemático, esto se evidencia con el parámetro α que es la mínima demanda por cubrir de cada servicio. Este no tiene una afectación significativa, ya que siempre se busca atender lo máximo posible con la capacidad existente.

Para trabajos futuros, se puede considerar el uso de un presupuesto de inversión gubernamental para la red de instalaciones de salud, donde se consideren parámetros de costos de apertura de nuevas instalaciones, mejoramiento de estas o aumento de recursos para lograr cumplir la demanda total de la región. Esto ayudaría a fortalecer la red hospitalaria para afrontar cambios demográficos de años futuros como pandemias, emergencias sanitarias, desastres naturales, entre otras situaciones donde se requiere una óptima capacidad de respuesta (cercanía, capacidad, tiempo de espera, accesibilidad, entre otros). Adicionalmente, también se puede considerar la disponibilidad del recurso humano para el cálculo de las capacidades de las instalaciones.

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Multicriteria analysis by the PROMETHEE-SAPEVO-M1 method: a decision analysis for the closure of a bank agency

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Abstract. The economic development of a company is directly linked to its capacity for technological innovation and the improvement of its products and services. In this scenario, the article presents a case study related to *Banco do País*, a centenary banking organization operating in Brazil. With the technological advance present in its activities, the company identified that its massive number of services agencies gradually became irrelevant for the purpose of the company. The paper addresses a decision-making process regarding the identification of an agency that has low performance and is conducive to the closure of its activities in a county in Rio de Janeiro. In the decision analysis, the PROMETHEE-SAPEVO-M1 method is performed, enabling a transparent assessment with data of different natures. For the application of the modeling, a web platform is implemented, allowing a clear evaluation through its numerical and graphic analysis, providing the identification of the most favorable agency for closure, without loss of effectiveness and enabling the allocation of reduced costs to the improvement of services and digital channels of the company.

Keywords: Decision-making, Multiple Criteria Decision Analysis, PROMETHEE, Bank agencies.

1 Introduction

The technological advance of recent years has established new trends in the organizational world, where the technologic innovation allowed the emergence of new business models, carrying the urgency of a digital transformation into companies [1]. In this context, the Banking segment has been one of the departments that most invests in Information Technology (IT), where Alves and Galegale [2] exposed that, during 2018 in Brazil, 14% of technology expenditures made in the country, have been done by banking organizations.

According to Oliveira and Magagolli [3], technological innovation in banking services allows the client to enjoy the same services offered by agencies, in a faster, easier, and safer way. As registered by FEBRABAN (Brazilian Federation of Banks), considering 78.9 billion financial transactions made in Brazil in 2018, approximately 60% of these were executed through mobile and internet banking [4].

In this scenario, the organization *Banco do País*, an adapted name for the study purpose, is a centenary group active in Brazil, where has been identifying a relative demand reduction regarding the services made in their agencies, and an increase of transactions made through digital environments. Prospecting a scenario of greater reduction in the services of bank agencies, the need to reduce costs arose, through the closure of activities in agencies that have been registering low profitability, absence, low representativeness, etc.

Through technology investments, the banks can obtain gain in market share and reduction of marginal costs [5]. Thus, the reduction of costs in physical services in some agencies would enable the *Banco do País* to obtain an effectively increase, and improvement of services in its digital channels. In a decision-making analysis, the perception of the problem gains new dimensions, incorporating new facts from the underlying reality, leading to a better understanding of the problem [6].

For the closure of an agency to be done effectively, without harming the banking organization and its customers, it is necessary an analysis that enables to measure the efficiency level of the agencies under evaluation, not only considering the profitability of agencies, but other factors of influence [7]. Based on the methods and application from Operational Research (OR), it is possible to solve real problems in different areas [8]. In this context the Multiple Criteria Decision Analysis (MCDA) allows the understanding and structuring of a problem in complex environments, considering uncertainty and risk, transparently [9].

The MCDA methods can be understood as techniques that enable the structuring and analysis of problems, providing the establishment of preference between the alternatives under qualitative and quantitative criteria, which are usually conflicting [10]; where the importance of the criteria is defined by the decision-making agents in an interactive process with other technical-political actors[11]. It is noteworthy that these methods do not aim to present a definitive solution and solve all kinds of problems, but to support the decision-making process meeting the requested constraints, within an analyzed context [12].

1.1 Questions and Objectives

The study aims to present a decision-making analysis based in MCDA concerning the organization *Banco do Pais*, in search to identify a favorable agency, in a specific area, to end its services, providing the cost reduction to the bank. To support the analysis, the new MCDA method PROMETHEE-SAPEVO-M1 will be implemented, by the moment that its axiomatic structure is favorable to the problem in context, enabling to analyze qualitative and quantitative data. Also, a web platform based on the method will be worked, providing an effective and assertive implementation.

The article is structured into five sections. After the introduction, section 2 explores some MCDA concepts and presents the origin of the method applied. Section 3 exposes in detail the axiomatic structure of the PROMETHEE-SAPEVO-M1 method. Section 4 is dedicated to the case study, exploring all steps of the decision-making process. Section 5 concludes the research findings.

2 Multiple Criteria Decision Analysis (MCDA)

The MCDA methods have received attention among decision support tools, due to their robustness analysis, enabling the evaluation of complex cases in an effective way [13]. An MCDA methodology should enable an integrated algorithm, providing an analysis structure that allows the evaluation of qualitative and quantitative variables, making possible the representation of the subjectivity and preferences of the decision-maker in a scenario with accurate and inaccurate data[14].

Regarding a quantitative analysis, the PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluations), proposed by Brans, Vincke, and Mareschal [15], is related to a hierarchical relation model where the preferential order of the variable in each criterion evaluated is normalized by a preference function. In this method, considering cardinal data, the decision-maker should establishes the preference degree between the criteria, defining if each one is a criterion of benefit (maximization) or cost (minimization), and which preference function will be applied [16].

Providing a qualitative analysis, the SAPEVO-M method (Simple Aggregation of Preferences Expressed by Ordinal Vectors - Multi Decision Makers), an extension of the SAPEVO method, proposed by Gomes, Mury, and Gomes [17], makes possible the evaluation data by ordinal inputs, designed to problematics that aim to clarify the decision-making process by the clustering of actions in equivalents classes, ranking to the preferences of the decision-maker.

2.1 The PROMETHEE-SAPEVO-M1 method

The method was developed by the integration of two MCDA methods, they are PROMETHEE and SAPEVO-M. The algorithm procedure is based on the axiomatic structure of the PROMETHEE method integrated to ordinal evaluation presents in SAPEVO-M, enabling to evaluate both quantitative and qualitative natures, in a mono decision analysis [18].

The method provides a complete analysis composed of a criteria evaluation set by a pairwise comparison based on an ordinal scale, and three different models of results analysis in relation to the preferences obtained, along with an intra-criterion analysis by veto threshold.

3 PROMETHEE-SAPEVO-M1 procedure

The evaluation process is structured into a matrix (Criterion x Alternative) (1), composed by a set of alternatives A, where $a_i \in A$, $i = 1, \ldots, n$, evaluated under a set of qualitative criteria h, $h = 1, \ldots L$, and a set of quantitative criteria j, $j = 1, \ldots k$.

	a_1	a_2	a_3	...	a_n
h_1	a_{11}	a_{21}	a_{31}	...	a_{n1}
h_L	a_{1L}	a_{2L}	a_{3L}	...	a_{nL}
j_1	a_{11}	a_{21}	a_{31}	...	a_{n1}
j_k	a_{1k}	a_{2k}	a_{3k}	...	a_{nK}

(1)

3.1 Alternatives evaluation

Considering the presence of qualitative and quantitative criteria, first the set A is performed concerning qualitative criteria h, $h = 1, \ldots L$. The process is characterized by a pairwise comparison between the alternatives regarding each criterion from set h. The analysis is based on the preference evaluation present on an importance scale, table 1.

Table 1. Importance scale.

Absolutely worse	**-3**
Much worse	**-2**
Worst	**-1**
Equivalent	**0**
Best	**1**
Much better	**2**
Absolutely better	**3**

In each qualitative criterion evaluated, it is obtained a matrix of preference relation between the elements belonging to the set A. By the equation (2), the punctuation is normalized, obtaining an importance degree of each alternative in a specific criterion.

$$v = \frac{\sum a_{ih} - \min a_{ih}}{max\ a_{ih} - \min a_{ih}} \tag{2}$$

After the normalization process and based on PROMETHEE procedure, they alternatives are submitted to a maximization evaluation $P_h(a_1, a_2) = P(d) = f(a_1) - f(a_2)$. With a new matrix composed by the difference between each pair from A, the differ-

ences are normalized by a function with linear variation (3), then the final preference degree is obtained, representing the preference relation relationship [0,1].

$$P(d) = \begin{cases} d/1 & d \leq 1 \\ 1 & d > 1 \end{cases} \quad (3)$$

The evaluation process regarding the quantitative criteria *j*, *j* = 1, ... *k*, it is sustained the PROMETHEE procedure, where for each quantitative criterion, it is necessary to specify a general preference function (P_j: *A x A* → [0,1]).

Comparing the alternatives a_1 and a_2 from set *A*, $P_j(a_1, a_2) = P(d)$ represents the preference degree of a_1 over a_2 according to the criterion *j*. When the criterion needs to be maximized, uses $P(d) = f(a_1) - f(a_2)$ to define a preference function. If it is necessary to minimize the criterion, $P(d) = f(a_2) - f(a_1)$ is used as preference function.

As exposed in [19], six types of preference function have been proposed to normalize the values obtained from the differences between the alternatives [16], they are *Usual*, *U-shape*, *V-shape*, *Level*, *V-shape I*, and *Gaussian*. According the attribution of criterion, thresholds may be defined, for more details about which function to select, please consult [20].

3.2 Criteria weights

The weights set considers the qualitative and quantitative criteria only in one set *j, j = 1, ..., L + k*. Using the ordinal scale presented in the table 1, the preference relation between the criteria is performed. In this evaluation, two variables called *maximum sum* and *minimum sum* is considered, enable the normalization of punctuation.

The *maximum sum* is obtained by *x = (n-1). 3*, representing the highest possible preference punctuating sum of each criterion, as closer a criterion is to *maximum sum*, greater will be its dominance in the set. In other hands, *minimum sum* is obtained by *x = (n-1). -3*, representing the minimum value possible within that assessment, as lower be the value and its closer to the *minimum sum*, the criterion will represent a little importance in the set.

The values obtained in the evaluation will be normalized by equation (4). After the normalization, each degree will be submitted to equation (5), providing the weights according to their respective criteria.

$$v = \frac{\sum c_{ij} - (max\ sum)}{(max\ sum) - (min\ sum)} \quad (4)$$

$$w(c_j) = \frac{v(c_j)}{\sum v(c_j)} \quad (5)$$

In the end of procedure, a global index preference π (a_1, a_2) is obtained, indicating the preference degree of alternative a_1 over a_2, considering the weights assigned to each criterion, where (6):

$$\pi(a_1, a_2) = \sum_{j=1}^{k+l} P_j(a_1, a_2) w_j \quad (6)$$

3.3 Preference Analysis

Composed by three different formats of manipulation, the preference analysis is integrated by a Partial outranking, Complete outranking, and an outranking by intervals.

The Partial outranking is evaluated by the positive outranking flow (7) and negative outranking flow (8), representing how a_1 outranks the other alternatives and how a_1 is outranked by the other options. How higher be the positive flow and lower be the negative flow, more favorable will be the alternative, where (9) (10) (11):

$$\phi^+(a_1) = \frac{1}{n-1}\sum_{x \in A} \pi(a_1, x) \tag{7}$$

$$\phi^-(a_1) = \frac{1}{n-1}\sum_{x \in A} \pi(x, a_1) \tag{8}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\begin{cases} \phi^+(a_1) > \phi^+(a_2) \text{ and } \phi^-(a_1) < \phi^-(a_2), \text{or} \\ \phi^+(a_1) = \phi^+(a_2) \text{ and } \phi^-(a_1) < \phi^-(a_2), \text{or} \\ \phi^+(a_1) > \phi^+(a_2) \text{ and } \phi^-(a_1) = \phi^-(a_2); \end{cases}$ (9)
- a_1 is indifferent to a_2 ($a_1 I a_2$) *if* $\phi^+(a_1) = \phi^+(a_2) \text{ and } \phi^-(a_1) = \phi^-(a_2);$ (10)
- a_1 is incompatible to a_2 ($a_1 R a_2$) *if* $\begin{cases} \phi^+(a_1) > \phi^+(a_2) \text{ and } \phi^-(a_1) > \phi^-(a_2), \text{or} \\ \phi^+(a_1) < \phi^+(a_2) \text{ and } \phi^-(a_1) < \phi^-(a_2); \end{cases}$ (11)

The Complete outranking is based in the net outranking flow (12), in this case, how higher be the net flow, more favorable is the alternative, where (13) (14):

$$\phi(a_1) = \phi^+ a_1 - \phi^- a_1 \tag{12}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\phi(a_1) > \phi(a_2)$ (13)
- a_1 is indifferent to a_2 ($a_1 I a_2$) *if* $\phi(a_1) = \phi(a_2)$ (14)

The third model of evaluation, consisting in an interval procedure [$x(a_1)$, $y(a_1)$] (15), based in a standard error value, defining a complete outranking by intervals, where (16) (17):

$$\begin{cases} x_{a_1} = \phi(a_1) - \alpha\sigma_{a_1} \\ y_{a_1} = \phi(a_1) + \alpha\sigma_{a_1} \end{cases} \tag{15}$$

- a_1 is preferable to a_2 ($a_1 P a_2$) *if* $\phi(a_1) > \phi(a_2)$ (16)
- a_1 is indifferent to a_2 ($a_1 P a_2$) *if* $\phi(a_1) = \phi(a_2)$ (17)

3.4 Intra-criterion Analysis

The intra-criterion analysis by veto threshold suggests an equivalence between alternatives with low performance (a_x) and high performance (a_y) in global analysis, from the moment that a_x presents a strict preference over a_y in a specific criterion c_j.

The veto v_j does not influence the outranking flows, but the analysis works as additional information to the decision-making process, where $v_j \geq p_j \geq q_j$. For qualitative criteria $v_h = 1$, and for quantitative criteria $v_j = max(a_{ij})$. If a preference threshold (p_j) be set and it is greater than v_j, the veto becomes equivalent to preference $v_j = p_j$.

4 Case study

The organization in context is a century-old company and one of the leaders as a banking organization in Brazil with more than four thousand agencies in the country. The institution covers various types of financial services, distributed in investments, insurance, credits, payments, currency trading, etc.

The study was carried out in the state of Rio de Janeiro, analyzing five agencies presented in a specific county from the city. Although, in the last years, the company has been registering a demand reduction regarding the services provided in the region, due to the viability of services through digital platforms. Figure 1 exposes the demand reduction related to the number of services registered between the semesters 01/2018 and 01/2019.

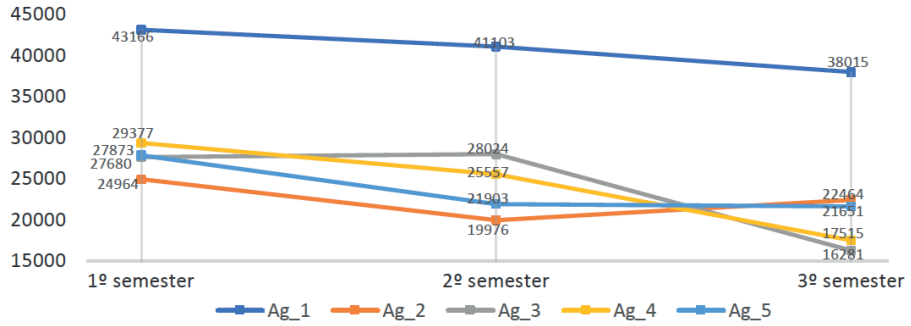

Fig. 1. Graph of number of services performed in the semesters 01/2018, 02/2018, and 01/2019.

Presenting an expressive demand reduction and handling with high fixed costs, it was considered to reduce costs by closing one of the agencies in the region, but keeping employers and customers in other agencies. In search of an effective assessment, the PROMETHEE-SAPEVO-M1 method was applied, making possible the identification of the main criteria of influence and enabling a detailed analysis.

The analysis is composed of five agencies, named: *Ag_A*, *Ag_B*, *Ag_C*, *Ag_D*, and *Ag_E*. The alternatives were evaluated under a set of seven criteria, being three qualitative and four quantitative, as presented in table 2. To enable effective implementation of the method to the case, the web platform [21] based on the method was worked, performing a friendly interaction and providing numerical and graphical results.

Table 2. Criteria for evaluation.

Criteria	Nature	Description
Coverage area	Qualitative	Criterion that considers in its assessment the distance between agencies, local competition, and region security;
Regional economic potential	Qualitative	Variable related to the proximity of commercial and business areas, public agencies, etc;
Profitability	Qualitative	Representation of the profitability of the agencies, however, by confidential, the criterion is evaluated qualitatively;
Average monthly cost	Quantitative	Criterion composed of costs with energy, water, rent, and property tax, the values are presented in thousands of reais (R$);
Number of services	Quantitative	Approximate number of services provided in the first semester of 2019, the amounts are in thousands;
Demand reduction	Quantitative	Demand reduction percentage in the semesters 01/2018 and 01/2019;
Representativeness	Quantitative	Representation of the representativeness of each agency in the county.

Identified the criteria and alternatives, the evaluation matrix for the case was built and represented in table 3, exposing numerical and qualitative data of each alternative under each criterion. Regarding the quantitative criteria, also the generalized functions and parameters for normalization were defined.

Table 3. Evaluation matrix for case study.

Criteria	*Ag_A*	*Ag_B*	*Ag_C*	*Ag_D*	*Ag_E*
Coverage area	Excellent	Poor	Poor	Excellent	Poor
Regional economic potential	High	Medium	Low	High	Low
Profitability	High	High	Low	Low	Medium
Average monthly cost (R$)	115.97	33.32	39.6	48.21	46.39
Number of services (Qty)	38	22.4	16.1	17.5	21.65
Demand reduction (%)	12	10	41	40	22
Representativeness (%)	32.8	19.4	14	15.1	18.7

4.1 Method implementation

By the web platform, it is indicated and named the alternatives and criteria. The software works in the same axiomatic structure of the method, evaluating first the alternatives under qualitative criteria. As exposed in figure 2, for the criteria *Coverage area*, *Regional economic potential*, and *Profitability*, it is realized a pairwise comparison between the alternatives in each criterion, establishing the preference relation based on the ordinal scale presented in section 3.1.

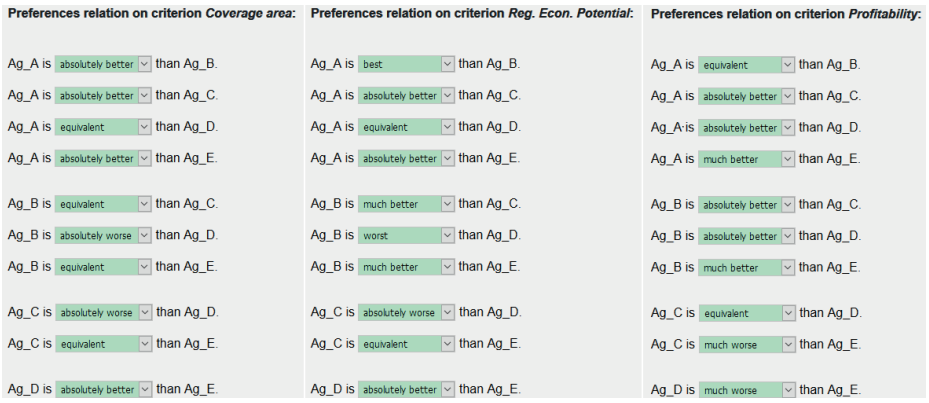

Fig. 2. Evaluation of alternatives under qualitative criteria, PROMETHEE-SAPEVO-M1 Software web.

Following the procedure, the alternatives were evaluated under the quantitative criteria. In each criterion was indicated the numerical data of each alternative, defined if it was a criterion of cost (minimization) or benefit (maximization), and established the preference function for normalization procedure. In figure 3, all data are exposed, observing that in the inferior area is set the parameters of each function selected, composed by thresholds of preference and indifference, where is established the limits for strict preference and non-preference respectively.

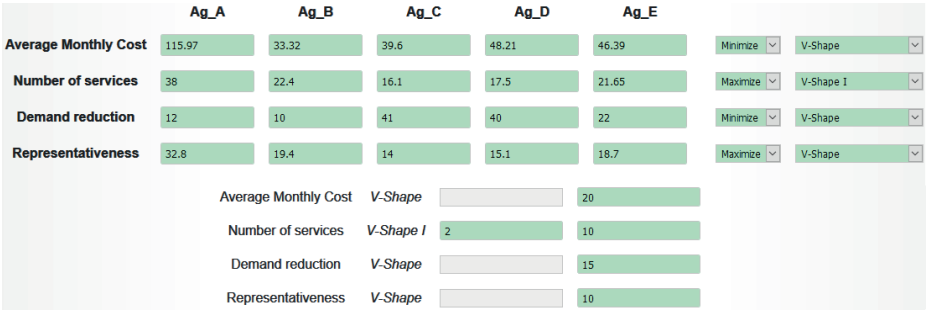

Fig. 3. Evaluation of alternatives under quantitative criteria, PROMETHEE-SAPEVO-M1 Software web.

Finished the alternatives evaluation, the procedure follows comparing the criteria in search to obtain the preference relation and the weight respective to each one. In the software, the process is similar to qualitative evaluation, just indicating the preference relation between each criterion. In table 4 is presented the punctuation of each criterion along with the final weights obtained based on the variables of *maximum sum* and *minimum sum*.

Table 4. Matrix of importance relation and weights obtained.

maximum sum = 18
minimum sum = -18

	Coverage area	*Reg. potential*	*Profitability*	*Average cost*	*Numb. services*	*Demand reduc.*	*Representati.*		*Punctuation*		*Normalized punctuation*		*Final weights*
Coverage area	0	1	-2	-2	-1	-2	0	=	-6	=	0.333	=	0.095
Regional ec. potential	-1	0	-3	-3	-2	-3	-1	=	-13	=	0.139	=	0.040
Profitability	2	3	0	0	1	0	2	=	8	=	0.722	=	0.206
Average monthly cost	2	3	0	0	1	0	2	=	8	=	0.722	=	0.206
Number of services	1	2	-1	-1	0	-1	1	=	1	=	0.528	=	0.151
Demand reduction	2	3	0	0	1	0	2	=	8	=	0.722	=	0.206
Representativeness	0	1	-2	-2	-1	-2	0	=	-6	=	0.333	=	0.095

Once obtained the weights, the preference relations expressed during the alternative evaluation are weighted. As an aggregation process, the global index preference is built, enabling to perform the positive, negative, and net outranking flows. Using these flows, it is possible to obtain the final ranking in search to identify the most favorable alternative in context. The values are exposed in figure 4.

	Ag_A	Ag_B	Ag_C	Ag_D	Ag_E	Positive Flows	Net Flows	Intervals (standard error = 0.096)	
Ag_A	0	0.051	0.113	0.094	0.089	0.347	0.227	x = 0.131	y = 0.323
Ag_B	0.033	0	0.091	0.094	0.062	0.28	0.214	x = 0.118	y = 0.31
Ag_C	0.029	0	0	0.013	0.01	0.052	-0.235	x = -0.331	y = -0.139
Ag_D	0.029	0.015	0.023	0	0.019	0.086	-0.173	x = -0.269	y = -0.077
Ag_E	0.029	0	0.06	0.058	0	0.147	-0.033	x = -0.129	y = 0.063
Negative Flows	0.12	0.066	0.287	0.259	0.18				

Fig. 4. Evaluation of alternatives under quantitative criteria, PROMETHEE-SAPEVO-M1 Software web.

4.2 Results analysis

As detailed in section 3, the PROMETHEE-SAPEVO-M1 method enables three models of results analysis, based on a partial, complete, and intervals outranking. All performances are analyzed by the graphic representation of each model of analysis in figure 5. Remembering that the partial ranking is based on the positive and negative flow, the complete ranking is based on the net flows, and the ranking by intervals is built by the lower and upper limit, with all values detailed in figure 4.

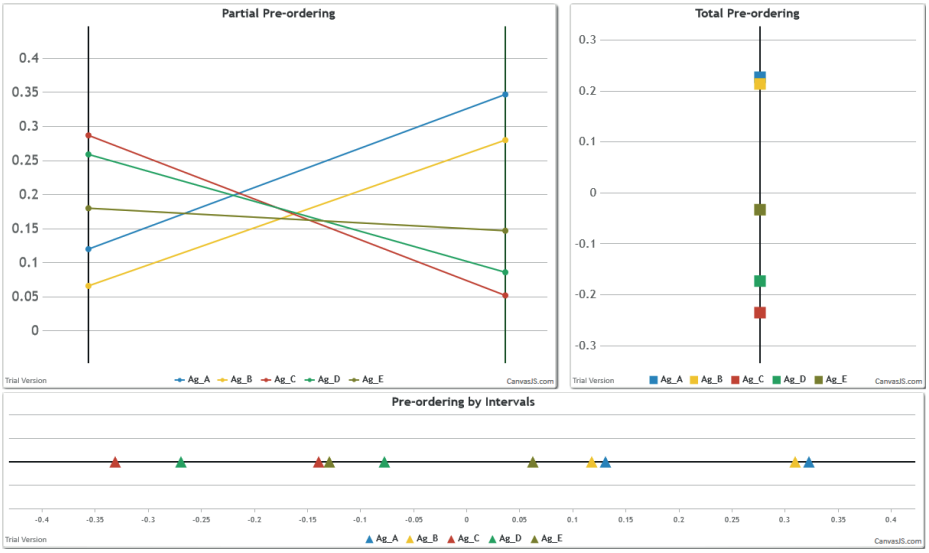

Fig. 5. Preference analysis charts, PROMETHEE-SAPEVO-M1 Software web.

In the first analysis model, the partial outranking, it was identified that the alternatives *Ag_A* and *Ag_B* obtained the best performances, both being preferable as the alternatives *Ag_C*, *Ag_D*, and *Ag_E*, but incompatible with each other, as exposed by the parallel line in figure 5. On the other hand, the alternative with the worst performance was *Ag_C*.

In the sequence, the complete outranking indicates the final ordering from the most favorable to the least favorable alternative. In this context, the best performance ranking obtained was: *Ag_A*, *Ag_B*, *Ag_E*, *Ag_D*, and *Ag_C*. Although, from the chart analysis, the proximity of the results between the alternatives *Ag_A* and *Ag_B* is noticeable.

In the third evaluation model, with the standard error value of 0.096, as exposed in figure 4, the intervals of the alternatives were generated by the lower and upper limits. In the analysis, it is noticeable that the agencies with the best performances remain *Ag_A* and *Ag_B*, indicating preference relation among the other alternatives under analysis, including, in this evaluation model, these agencies started to indicate a relationship of indifference among themselves. The agencies *Ag_C* and *Ag_D* continued to present the worst performance regarding the other alternatives from the set.

In search of efficiency regarding the analysis model, a "distillation" process of the alternatives was carried out, by the moment that the software worked enables this feature. In the procedure, the *Ag_A* agency was removed, for presenting the best result and looking to identify whether this alternative does not influence the final outranking. The new outranking flows and the interval analysis chart are exposed in figure 6.

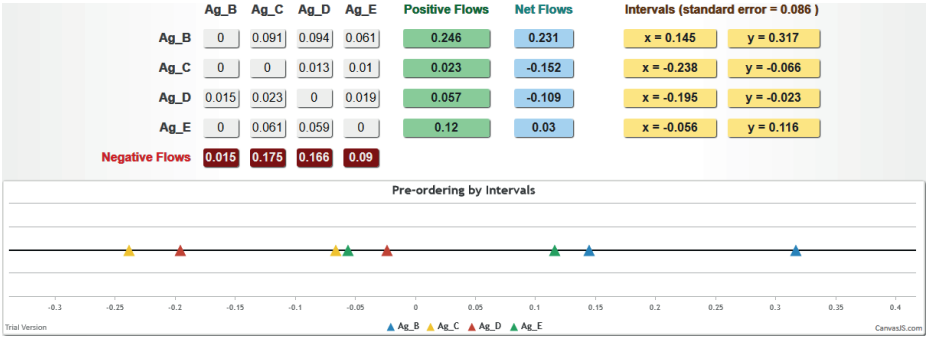

Fig. 6. New outranking flows, after distillation process along with the interval analysis charts, PROMETHEE-SAPEVO-M1 Software web.

After the distillation, it is noticeable that the preferences remain, presenting only small variations regarding the outranking flows. In this case, the agencies *Ag_C* and *Ag_D* continued to present the worst performance. In this context, the agency selected for closure was the alternative *Ag_C*, presenting the lowest performance in the three forms of analysis and prospecting a future development of the organization, and comparing to agency *Ag_D*, the *Ag_C* is not favorable for its characteristics in the qualitative criteria, as exposes the intra-criterion analysis in figure 7.

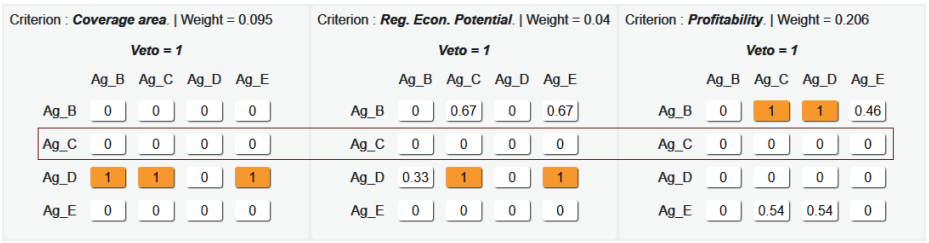

Fig. 7. Intra-criterion analysis in qualitative criteria after the distillation procedure, PROMETHEE-SAPEVO-M1 Software web.

With the analysis obtained, it is interesting to note that in the analyzed region, a cost reduction of 13.96% was acquired, with an approximate annual deduction of R$ 475 200.00. Considering that *Banco do País* has more than 4000 agencies in Brazil, the analysis is favorable to be made in other counties of the country, in search to contain costs in a macro way.

5 Conclusion

This paper purposed to present a case study based on the organization *Banco do País*, witnessing a scenario in which the closure of one of its agencies in a specific region, enabled the cost reduction through the identification of factors that allowed this action without loss of effectiveness.

In this case, a decision-making process was carried out through a MCDA methodology, listing five agencies and evaluating them under seven criteria, ranking them according to their respective performances, and identifying the most favorable for closing.

For the evaluation, the PROMETHEE-SAPEVO-M1 method was applied through a web platform, allowing the analysis of data from different natures and a structured format for obtaining weights to the criteria. The implementation proved to be efficient and effective, allowing a transparent evaluation, identifying the criteria of greatest influence, and the agencies that were most sensitive to them. In the end, the alternative that presented the lowest performance was identified, being select as the most favorable alternative for closure, where this action does not negatively influence the organization.

The selected alternative allowed a reduction of 13.9% in the costs of the company, considering the region evaluated. In this way, it is favorable for Banco do País to be carrying out a global analysis, in all its regions of operation, identifying agencies that present absence, demand reduction, and low profitability, allowing the cost reduction and providing resources to improve technologies and quality of services.

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Development of a methodological proposal for the creation of strategic maps incorporating feasible futures

Abstract

This paper presents a methodology for building a strategy map of a Balanced Scorecard (BSC) that considers possible scenarios. A strategy maps is a representation of the strategy of a company and consists of strategic objectives linked by causal relationships between them. The objectives are grouped into four perspectives: financial, clients, internal processes and growth & development. One of the limitations of strategy maps is that they are built only for one future scenario. They do not take into account that the future may change. The contribution of this work is that we propose a method that allows strategy maps to change as scenarios change. It uses the Analytic Network Process (ANP) to model a strategy map. The method was implement in two manufacturing companies.
Keywords: Strategic planning, strategy map, scenarios.

1. Introduction.

The strategic planning explores and projects the possible future changes of the environment to define the strategies. The scenarios prospectively design possible futures and, consequently, the union of these two tools represents an enormous potential to improve the way of facing the future. The objective of this work is to develop a methodological proposal to create strategy maps that consider probable futures. The methodology integrates Scenarios with the Balanced Scorecard (BSC) (Kaplan & Norton, 2004), in order to relate and reflect the dynamics of environmental changes with the strategic objectives and with the strategies define d by the organizations. The methodological approach is qualitative based on the design of the case study, because it seeks to validate a methodology, the generalization of the case study does not imply that in similar industries the same results will be obtained, but it is studied how plausible is the proposed methodology to formulate strategy maps for the management and administration of strategies in organizations. Defines three Scenarios, the strategy map is constructed for each one of them, using the Analytic Network Process

(ANP) (Saaty, 2001) to determine the weight of the causal relationships in each scenario. The probabilities of occurrence of each scenario are assigned using AHP, finally achieve a "Global Scenario" that incorporates the three initially defined scenarios. Finally, the methodology is established to adjust and adapt the objectives and established strategies. This methodology was applied in two companies in Chile. The evaluation of the companies with respect to the intervention carried out coincides in that in that it is a real and valuable contribution to improve their business management.

This work is an extension of the method proposed by Gonzalez et al. (2019) who use the Analytic Hierarchy Process (Saaty, 1996) to model a strategy map under various scenarios. The limitation of that work is that it only allows hierarchical strategy maps, which are not common in real situations. Apart from that paper, the literature on the subject is scarce. The only other paper found was the one authored by Buytendijk et al. (2008), who created strategy maps for various scenarios and provides a method to combine them. It is not applied in any company.

2. The ANP model.

The strategy map is modelled using an ANP model, as shown in Figure 1.

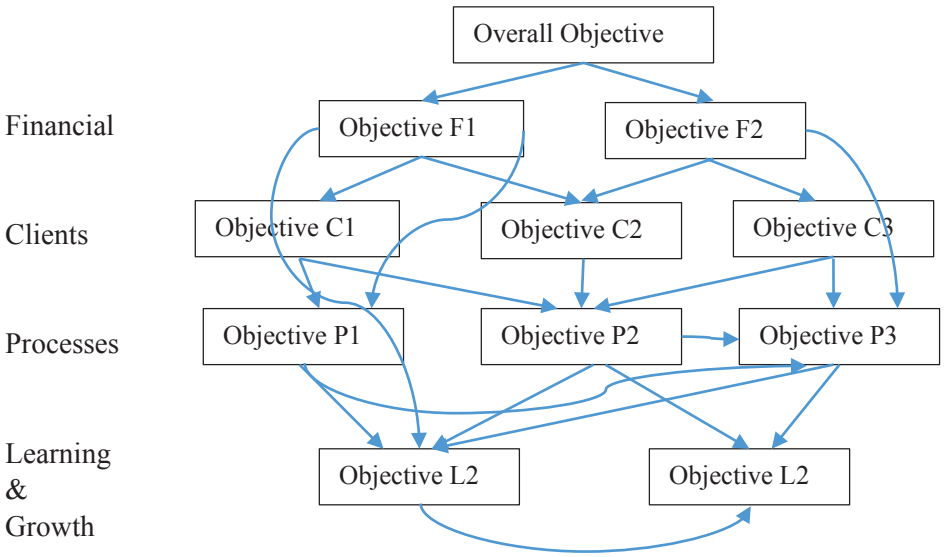

Figure 1: Representation of a strategy map.

The steps of the method are:

1. Generate scenarios
2. Build strategy map for each scenario
3. Assign weights to every relationship in the maps, using ANP.
4. Select the most important relationships in each strategy map using a threshold value.
5. Assign priorities to each scenario using AHP.
6. Combine strategy maps.

The last step is carried out by analyzing which strategic objectives are common in the scenarios and which relationships are also important in them. In this way, the company will design its strategies and their respective action plans based on this strategic map, which are valid in any of the three scenarios that appear, so that their actions represent the best option to take.

Annually, the company reviews and studies the evolution and projection of the behavior of environmental variables. Depending on the observed behavior and the estimated projection of these variables, certain objectives must be incorporated and prioritized in order to make the necessary adjustments to maintain and improve their competitive position.

3. Application

The method was applied in two companies. Company A manufactures of special glass elements used for laboratories, whereas company B Distributor and marketer of laboratory equipment mainly for the area of research and quality control and industrial processes.

After the application, managers were ask about their opinion about the proposed method. They were very happy because it allows them to look at different possible futures and be prepared for them. In the other hand, they stated that the discussion generated was very useful, because it allows considering the viewpoints from people from different areas.

4. Conclusions

The methodology developed allows companies to obtain a broad vision of their future prospects. The generation of the most probable scenarios provided the company with a vision and understanding of the relevant, sensitive variables in its environment, as well as their impact on the defined strategies.

Finally, it is concluded that the strategic maps should be based on the environmental scenarios, because the environment impacts the company in the definition of its strategic objectives and therefore impacts the strategic map that represents them and consequently their strategies and your action plans.

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Toma de decisiones multicriterio para identificar los procesos de mayor impacto en la continuidad operacional en una empresa sanitaria en contexto de pandemia

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Resumen. En la actualidad la planificación de las medidas de control para la continuidad del negocio y la resolución de imprevistos son elementos esenciales que las compañías de servicios básicos deben gestionar para disponer del buen funcionamiento de sus procesos en el caso de una interrupción. El reconocimiento de los procesos de mayor impacto para la organización es vital para el desarrollo sostenible y/o incluso para la supervivencia de cualquier organización. Un estudio de caso ha sido llevado a cabo en una empresa sanitaria de Chile priorizando los procesos de mayor impacto que podría permitir elaborar una política de prevención, lo que conlleva a un plan de inversiones. Para esto, se ha considerado cinco impactos al negocio como indispensables de ser contrastados para cada uno de los ocho procesos que posee la organización en estudio. Para la elaboración de esta priorización se aplica el Proceso de Jerarquía Analítica considerando opiniones de expertos y datos empíricos.

Palabras Claves: Proceso de Jerarquía Analítica, AHP, Impacto, Procesos, Empresa Sanitaria.

1 Introducción

Actualmente, la situación sanitaria que enfrenta el mundo y Chile deja de manifiesto la importancia de contar con medidas que apunten a salvaguardar la salud de todos quienes forman parte de la cadena productiva de la industria sanitaria.

Es por esto, que identificar los principales procesos a través de la evaluación de los impactos a los que ve expuesta la empresa sanitaria, permitirá conocer las amenazas trascendentales a la organización y fortalecer la capacidad para mitigarlas. Esto último, dará paso a que la organización genere una estrategia de mediano y largo plazo para asegurar la continuidad del servicio y tener mayor control en caso de sufrir interrupción en alguno de sus procesos.

Este documento propone un enfoque de criterios múltiples para identificar los procesos más relevantes en una empresa sanitaria, que podrían afectar la continuidad del servicio en base a su impacto legal, de imagen, financiero, medioambiental y social.

El Proceso de Jerarquía Analítica (sigla en inglés AHP) resulta adecuado para abordar este tipo de situación problema y ha sido bastante utilizado universalmente en problemas que presentan múltiples objetivos y valoraciones intangibles.

El estudio se basa en la aplicación del método a un caso real dentro de una empresa sanitaria en Chile.

2 Trabajos Anteriores

En lo que se refiere a trabajos anteriores, mencionamos los siguientes: Guan [1], que aplica el AHP al Business Impact Analysis (BIA) para orientar la aplicación de la organización del plan de gestión de continuidad de negocio a través del sistema de índice y computación científica, ya que el BIA utiliza métodos de análisis cualitativo y análisis de expertos, pero le falta apoyo teórico cuantitativo y computación científica.

Por otro lado, consideramos a Macuada [2], quien utilizó AHP para desarrollar un nuevo modelo de decisión multicriterio en base a los dictámenes de expertos para la identificación de los requisitos de dimensiones de alta prioridad para la automatización de plantas de tratamiento. El estudio proporciona una base para el establecimiento de prioridades y la toma de decisiones para la incorporación de un sistema automatizado para plantas de agua potable y aguas servidas.

Por último, se tiene en cuenta el trabajo de Yang [3], donde se propone como objetivo, extraer los aspectos y criterios para la evaluación y selección de criterios de un sitio de recuperación ante desastres en el área de las tecnologías de la información (TI) (disponibilidad del servicio, tiempo de recuperación, desempeño del servicio y otros).

3 Objetivos

El contexto de la problemática abordada comprende los procesos esenciales del negocio en una empresa sanitaria de Chile.

En la Figura 1 se muestran los principales procesos de la empresa sanitaria identificando aquellos que corresponden a la producción de agua potable, depuración de aguas servidas y relación con el cliente.

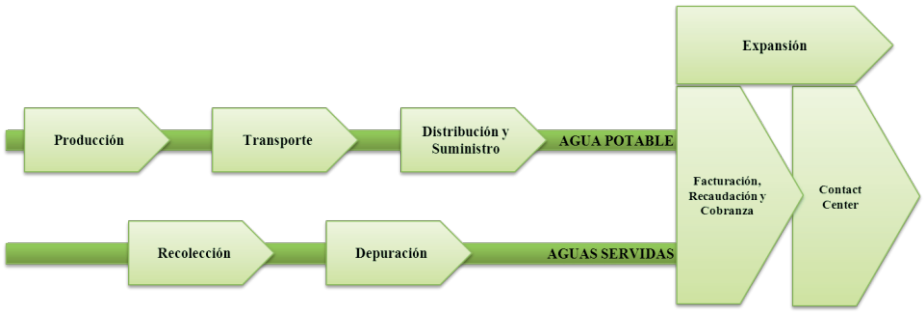

Fig. 1. Procesos Críticos de la Empresa Sanitaria.

4 Metodología de Investigación

La metodología de investigación utilizada está basada en estudio de caso aplicando el AHP [4, 5]. El planteamiento inicial comienza con la determinación de los factores más importantes (Legal, Imagen, Financiero, Medioambiental y Social) que afectan cada proceso a la empresa (Producción, Transporte, Distribución y Suministro, Recolección, Depuración, Facturación-Recaudación-Cobranza, Expansión, Contact Center. Esto permite diseñar una estructura jerárquica, donde las categorías críticas para cada nivel y sus relaciones se obtienen de la consulta a los expertos (Ingenieros de gestión de calidad, ingenieros de proyectos y miembros de la alta dirección).

5 Modelo Propuesto

El modelo de jerarquía para determinar la priorización de los criterios de impacto en los procesos del negocio está diseñado con tres niveles indicados en la Figura 2.

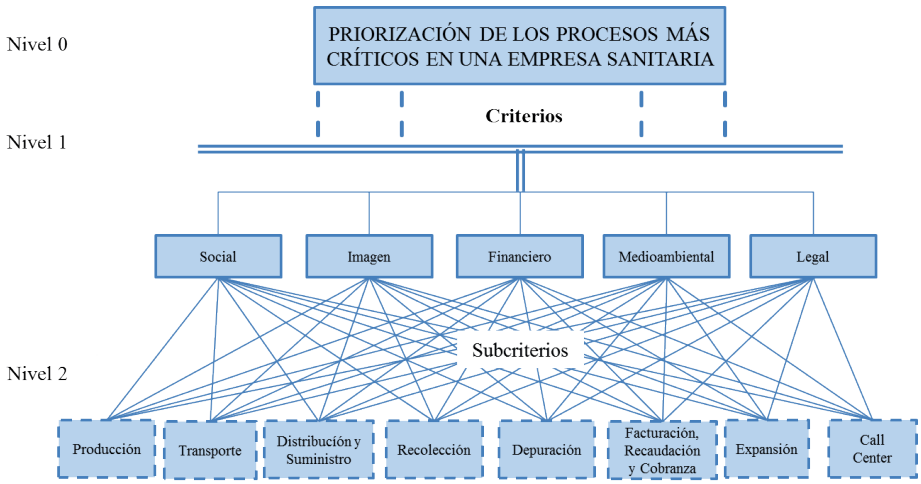

Fig. 2. Estructura Jerárquica Simplificada.

Los factores de decisión se basan en una evaluación comparativa con los procesos más críticos para la empresa, considerando todo lo relacionado a la entrega de servicio de agua potable y recolección de aguas servidas, procesos de cobranza y atención al cliente. En este punto, era posible ser testigo de ciertos tabúes existentes con relación a qué procesos impactan más en la industria bajo el contexto de pandemia. Una puntuación numérica se obtiene por el panel de expertos por referencia a una tabla con el fin de medir el estado actual de cada proceso.

6 Limitaciones

El modelo propuesto considera que no existe interrelación entre las variables. Por otra parte, los procesos críticos examinados fueron sólo los que la empresa en estudio requería evaluar.

7 Conclusiones

En el presente trabajo se ha presentado un problema real de priorización de procesos de mayor impacto en cadena productiva de la compañía, de manera de generar planes de prevención y hacer más eficiente la política de inversiones de la empresa sanitaria, utilizando el enfoque del AHP.

Dada la existencia de distintas variables de decisión para elegir qué procesos son más prioritarios, el desarrollo de un modelo de decisión utilizando AHP fue ventajoso, ya que se obtuvo un entendimiento profundo en los principales requisitos para generar una política de prevención acompañada de su respectivo plan de inversiones, y, a través del proceso de la importancia relativa, se obtuvo los procesos que deben ser considerados en primera instancia.

La priorización resultante señala que las inversiones debiesen estar abocadas en orden decreciente a: Producción, Recolección, Depuración, Distribución y Suministro, Transporte, Contact Center, Facturación – Recaudación – Cobranza y Expansión.

Los resultados de este estudio pueden ser considerados en empresas sanitarias que requieran evaluar los procesos que deben ser priorizados dentro de un plan de inversiones y mitigación de riesgos, buscando mejorar, dar continuidad a la operación y aumentar el valor de la compañía.

Agradecimientos

Un agradecimiento especial de los autores al Departamento de Investigación y Desarrollo Tecnológico (*Proyectos DICYT N ° 061817OH & 061817QL*) y al Departamento de Ingeniería Industrial de la Universidad de Santiago de Chile por el apoyo para la realización del estudio.

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Gestión de inventarios de partes de repuesto: Caso de estudio

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Resumen: La gestión del inventario tiene como objetivo determinar y controlar los niveles de inventario dentro del inventario físico, de modo que satisfacer la necesidad de disponibilidad de producto y minimizar los costos relacionados con el inventario deben estar bien equilibrados. En el sector automotriz, específicamente en la rama de autopartes, equilibrar costos y disponibilidad del producto es una ardua tarea. En esta investigación se buscan alternativas de solución a los problemas derivados de la falta de una adecuada gestión de inventarios, para una empresa de partes de repuesto automotriz en México. El objetivo de este trabajo es proponer una nueva política de inventario que permita minimizar los costos totales de inventario mientras, se satisface el nivel de servicio objetivo para los clientes de la empresa. Para llevar a cabo el objetivo, se cuenta con un análisis previo de datos de los productos seleccionados, a través de la demanda futura pronosticada mediante modelos ARIMA, para evaluar dos políticas de inventario (s, S) y (R, S). Las dos políticas permiten minimizar niveles y días de inventario, así como los costos asociados a excesos de inventario y manejo ineficiente de los mismos. Definida la mejor política de inventario se utilizó un sistema de reabastecimiento conjunto propuesto por Atkins y Iyogun en 1998, permitiendo que los artículos con baja demanda sean incluidos en los pedidos de artículos de mayor movimiento, eliminando así un costo de configuración mayor en un futuro cercano cuando el artículo de bajo movimiento alcance su punto de reorden.

Palabras clave: Gestión de inventarios; Demanda; Política de inventario; Punto de reorden; Cantidad económica de pedido.

Abstract. Inventory management aims to determine and control inventory levels within physical inventory, so that meeting the need for product availability and minimizing inventory-related costs must be well balanced. In the automotive sector, specifically in the auto parts branch, balancing costs and product availability is an arduous task. This research looks for alternative solutions to the problems derived from the lack of adequate inventory management for an automotive spare parts company in Mexico. The objective of this work is to propose a new inventory policy that allows minimizing total inventory costs while satisfying the target service level for the company's customers. To carry out the objective, there is a previous analysis of the data of the selected products, through the forecast future demand using ARIMA models, to evaluate two inventory policies (s, S) and (R,

S). The two policies allow minimizing inventory levels and days, as well as the costs associated with excess inventory and inefficient handling of the same. Once the best inventory policy was defined, a joint replenishment system proposed by Atkins and Iyogun in 1998 was used, allowing items with low demand to be included in the orders for items with greater movement, thus eliminating a higher configuration cost in the near future. When the low-moving item reaches its reorder point.

Keywords: Inventory management; Demand; Inventory policy; Reorder point; Economic order quantity

1 Introducción

La gestión y el control de inventarios representa una de las actividades más importantes en las organizaciones. Las organizaciones manejan bienes para su venta o su inclusión en la cadena de producción o suministro. El control de los costos y la determinación de políticas eficientes para el mantenimiento y la gestión de inventarios supone una disminución de los gastos derivados de su actividad logística o comercial y un crecimiento de sus beneficios [1].

La gestión del inventario tiene como objetivo determinar y controlar los niveles de inventario dentro de los sistemas de inventario físico, de modo que la necesidad de disponibilidad del producto y la necesidad de minimizar los costos relacionados con el inventario estén bien equilibrados [2]. Un objetivo es mantener los niveles de existencias lo más bajo posible para minimizar los costos y liberar capital de trabajo tanto como sea posible. Otro objetivo es proporcionar un alto nivel de servicio a los clientes para evitar el riesgo de pérdida de ventas en caso de inventarios insuficientes [1].

En general, se puede hablar de cuatro componentes fundamentales que determinan los sistemas de inventario y que dan lugar a diversas propiedades de estos. Estos componentes fundamentales son demandas, reposiciones, costos y restricciones [3].

Una cuestión importante de la gestión de inventario es encontrar una política de inventario óptima para controlar la reposición de producto en almacén y minimizar los costos relacionados con el inventario, mientras se mantiene un nivel de servicio para los clientes. Aquí, una política de inventario es un mecanismo que decide cuándo debe realizase un pedido de reposición de inventario, lo cual determina la cantidad de ordenar (cuánto) de qué producto.

En este trabajo de investigación se cuenta con información de demanda futura (previamente pronosticadas mediante modelos ARIMA (*Autoregressive Integrated Moving Average*) [4], para una empresa de repuestos de autopartes. La empresa en estudio es de origen mexicano. Comercializa autopartes de repuesto automotriz de suspensión y dirección a nivel nacional. Su marca tiene renombre en el sector como proveedor de partes de repuestos al mercado automotriz, así como importante distribuidor de autopartes automotrices en México, manejando alrededor de 1,000 productos para el mercado nacional. La empresa se considera dentro del ramo de repuestos de calidades equivalentes a la original. El problema de la empresa radica en no contar con una herramienta de gestión de inventarios eficiente en costos que le permita evaluar y controlar el sistema de inventarios de repuestos.

Con base en esta información de demandas proporcionada por la empresa en estudio, se determinaron las políticas de inventario adecuadas, de modo que se minimice el costo total de gestión del inventario. Una vez encontrada la mejor política de inventario se utiliza un sistema de reabastecimiento conjunto propuesto por Atkins y Iyogun en 1998 [5], permitiendo que los artículos con baja demanda sean incluidos en los pedidos de artículos de mayor movimiento, eliminando así un costo de configuración mayor en un futuro cercano cuando el artículo de bajo movimiento alcance su punto de reorden. Este trabajo se centra en el uso de sistemas probabilísticos de gestión de inventario, esto es, la demanda no es conocida con certeza y se aplican políticas de inventario para este tipo de demanda. Las políticas seleccionadas serán la política (s, S) (***s*-**punto de reorden, ***S*-**inventario meta) y la política (R, S) (***R*-**periodo de revisión, ***S*-**inventario meta). El objetivo es determinar la política óptima para el sistema de inventario, de modo que el costo total en todo el sistema se minimice mientras se satisface el nivel de servicio objetivo para los clientes. Los resultados obtenidos muestran que la política de inventario seleccionada mejora un 10 % en el manejo de inventario y un decremento en el costo por ordenar debido a un buen manejo de inventario.

El documento contiene cinco apartados, el siguiente a este es el apartado dos en el que se muestra la revisión de literatura necesaria para comprender la metodología a utilizar en el desarrollo del trabajo, la cual se encuentra en el apartado número tres. La descripción del caso de estudio y la aplicación de la metodología se presenta en el apartado cuatro, así como los resultados obtenidos de la aplicación de la nueva política de inventarios; finalmente en el apartado cinco se muestran las conclusiones.

2 Revisión de literatura

En la literatura el control de inventarios pretende contestar a tres preguntas fundamentales: ¿Con que frecuencia revisar el inventario?, ¿Cuándo reponer? y ¿Con qué cantidad? [6]. La primera pregunta se responde de acuerdo con la política de control de inventario que las empresas apliquen a sus inventarios. La segunda pregunta se puede responder de dos formas: i) se debe reponer el inventario cuando la cantidad de producto (*stock*) sea igual o menor a ***s*** (punto de reorden) unidades. ii) se puede reponer el inventario cada ***R*** (periodo de revisión) unidades de tiempo. Mientras que las posibles respuestas para la tercera pregunta son: i) se añaden al inventario siempre ***Q*** (cantidad fija de pedido) unidades, o bien ii) se repone una cantidad tal que, al incorporarla al inventario, el nivel de este alcanza el valor de ***S*** (inventario meta) unidades [4,5,6]. El objetivo principal de estas preguntas es brindar el nivel deseado de servicio al cliente a un costo mínimo. El primer modelo desarrollado para contestar la tercera pregunta se desarrolló hace diez décadas por Harris (1913) a este modelo lo llamo EOQ (*Economic Order Quantity*) [7].

Los modelos de inventarios se pueden clasificar en modelos determinísticos y estocásticos. Los modelos deterministas asumen una demanda y tiempo de entrega conocidos con certeza, por otro lado, los modelos estocásticos la demanda y tiempos de entrega no son conocidos con certeza [6]. El objetivo del modelo probabilístico es determinar el momento de emisión del reabastecimiento y la cantidad a pedir, sujeto a la incertidumbre de la demanda y/o cualquier otro parámetro [2].

Teniendo en cuenta lo anterior, se consideran las siguientes políticas de inventario: i) políticas de revisión continuas **(*s, Q*)** y **(*s, S*).** La política **(*s, Q*)** solicita una cantidad

fija de ***Q*** cada vez que la posición de inventario cae al punto de pedido ***s*** o inferior por otro lado la política **(*s, S*)** se produce cuando el *stock* decrece a ***s*** se ordena para elevar la posición del inventario hasta el nivel ***S***. ii) políticas de revisión periódicas **(*R, S*)** y **(*R, s, S*)**, la política **(*R, S*)** cada ***R*** unidades de tiempo, se ordena lo suficiente como para elevar la posición del inventario al nivel ***S*** [6]. Otra variable es el periodo de entrega (que se denota por ***L*** conocido como *lead time*), que representa el intervalo de tiempo que transcurre entre que se solicita un pedido hasta el instante en que dicho pedido se añade al *stock* [2].

Debido al componente aleatorio que tienen las demandas de piezas de repuesto, es necesario abordar sistemas de revisión con demanda probabilística, permitiendo el cálculo del *stock* de seguridad (***SS***), que amortigüe la demanda de repuestos; el cálculo del *stock* de seguridad será alimentado por el error que generan los pronósticos aplicados [4]. Para este caso de estudio se seleccionaron la políticas de revisión continua ***(s,S)*** y la política de revisión periódica ***(R, S)*** propuestas por [6], para control de inventarios con demandas probabilísticas.

Política (*s, S*): Este sistema de control de inventarios asume una revisión continua; y, al igual que el sistema (*s, Q*), se realiza un reabastecimiento cada vez que la posición de inventario cae al punto de pedido ***s*** o menor. Sin embargo, en contraste con el sistema (*s, Q*), se usa una cantidad de reabastecimiento variable, ordenando lo suficiente como para elevar la posición del inventario hasta el nivel ***S***. Si todas las transacciones de demanda son de tamaño unitario, los dos sistemas son idéntico porque la solicitud de reposición siempre se realizará cuando la posición del inventario esté exactamente en ***s***; es decir, ***S*** = ***s*** + ***Q*** [2]. Esta política fue abordada por [9], utilizando programación no lineal entera mixta para determinar los parámetros casi óptimos y, posteriormente utilizar programación lineal entera mixta para su comparación y mejorar el modelo.

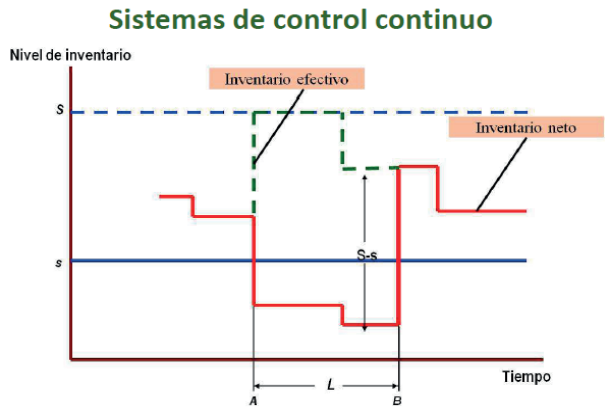

Fig. 1 Sistema de inventario (*s, S*). Fuente: Modificado de [2].

Para la aplicación de la política de gestión de inventarios de revisión continua (*s, S*) se debe hacer uso de las siguientes formulas propuestas por [2]:

Tamaño de pedido:

$$Q = EOQ = \sqrt{\frac{2AD}{vr}} \tag{1}$$

donde:

$$A = costo\ de\ configuración\ por\ ordenar$$

$$D = demanda\ anual$$

$$v = costo\ de\ producto$$

$$r = tasa\ de\ mantenimiento$$

Desviación estándar de los errores pronosticados sobre el tiempo de reposición L:

$$\sigma_L = \hat{\sigma}_1\sqrt{L} \tag{2}$$

donde:

$$\hat{\sigma_1} = desviación\ estandar\ de\ pronósticos$$

$$L = lead\ time$$

Función especial de distribución normal:

$$G_u(k) = \frac{Q}{\sigma_L}(1 - P_2) \tag{3}$$

donde:

$$P_2 = probabilidad\ o\ tasa\ de\ existencia\ del\ producto$$

Demanda esperada sobre el tiempo de reposición L:

$$\hat{x}_L = dL \tag{4}$$

donde:

$$d = demanda\ promedio\ mensual$$

Punto de reorden:

$$s = \hat{x}_L + k\sigma_L \tag{5}$$

donde:

$$k = factor\ de\ seguridad$$

Costo total relevante:

$$TRC = \frac{AD}{Q} + \left[\frac{Q}{2} + k\sigma_L\right]vr + \frac{D}{Q}(B_2 v)\sigma_L G_u(k) \tag{6}$$

donde:

$$B_2 = cargo\ fraccionado\ por\ unidad\ faltante$$

Política (*R, S*): Este sistema de control de inventarios asume una revisión periódica, también es conocido como un sistema de ciclo de reabastecimiento, es de uso común, particularmente en empresas sin control informático sofisticado. También se ve con frecuencia cuando los artículos se solicitan al mismo proveedor o requieren compartir recursos. El procedimiento de control es que cada ***R*** unidades de tiempo (es decir, en cada instante de revisión) se ordena lo suficiente como para elevar la posición del inventario al nivel ***S***. El sistema (*R, S*) ofrece una oportunidad regular (cada ***R*** unidades de tiempo) para ajustar el orden hasta el nivel ***S***, una propiedad deseable si el patrón de

demanda cambia con el tiempo. Las principales desventajas del sistema (*R, S*) son que las cantidades de reabastecimiento varían y que los costos de mantenimiento son más altos que en los sistemas de revisión continua [2].

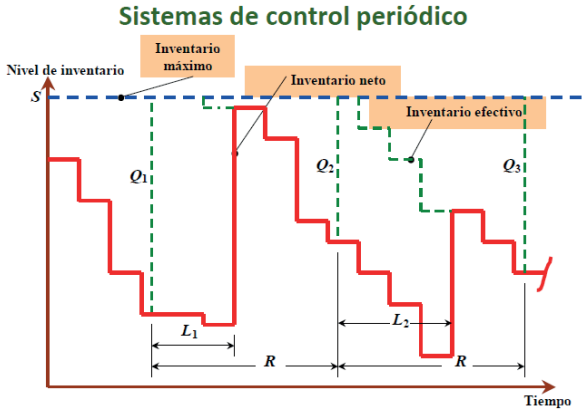

Fig. 2 Sistema de inventario (*R, S*). Fuente: Modificado de [2].

Para la aplicación de la política de gestión de inventarios de revisión periódica *(R, S)* se debe hacer uso de las siguientes formulas propuestas por [2]:

Demanda esperada sobre el tiempo de reposición L:

$$\hat{x}_{R+L} = d(R + L) \tag{7}$$

donde:

$$R = intervalo\ de\ revisión$$

Punto de reorden:

$$s = \hat{x}_{R+L} + k\sigma_{R+L} \tag{8}$$

donde:

$$\sigma_{R+L} = \sqrt{\frac{R+L}{2}} * \sigma_1\sqrt{R}$$

Costo total relevante:

$$TRC = \frac{A}{R} + \left[\frac{DR}{2} + k\sigma_{R+L}\right] vr + \frac{1}{R}(B_2 v)\sigma_{R+L} G_u(k) \tag{9}$$

Donde las variables que se integran a las ecuaciones 7, 8 y 9 tienen el mismo significado ya descrito en la política (*s, S*).

En general, se debe mantener cierta cantidad de producto en inventario para el funcionamiento eficiente de un negocio. Esa cantidad está condicionada o depende de la demanda que haya de los productos en el mercado. La demanda debe ser satisfecha con la cantidad de inventario almacenada. Los modelos clásicos de gestión de inventarios consideran que la demanda es conocida y constante. Sin embargo, esta situación en la que conocemos con precisión las demandas futuras es poco común en la práctica [3].

Estas dos políticas de inventarios propuestas para el caso de estudio han sido ampliamente estudiadas, para la gestión de diferentes tipos de inventarios, una revisión bibliográfica se realizó aplicando diferentes métodos para 2012 a 2015 para artículos perecederos [10]. Estudios para diferentes tipos de demandas se han realizado, utilizando programación no lineal entera mixta, heurísticos como *Silver-Meal* y el algoritmo de *Wagner-Whitin,* los cuales son prometedores para ciertos tipos de demandas [11].

Un sistema de reabastecimiento en conjunto se da cuando se piden varios artículos simultáneamente, en lugar de individualmente, esto con la intención de que el costo total al agregar más artículos de línea sea mucho menor que el costo total de pedir artículos individualmente, cuando los artículos son abastecidos por un mismo proveedor [9].

Un sistema de abastecimiento conjunto busca un equilibrio entre las decisiones de frecuencia de revisión del inventario y las cantidades a ordenar; logrando una coordinación de todos los productos (*ítems*), considerando que las ordenes se hacen a un solo proveedor [7]. Dentro de los sistemas de revisión para realizar el reabastecimiento conjunto, uno de ellos se adapta a las necesidades de la empresa en estudio, se trata de un sistema de revisión periódica sugerido por *Atkins y Iyogun* en 1998, quienes desarrollaron un algoritmo para realizar un reabastecimiento conjunto.

Este tipo de sistemas está orientado a generar ahorros en el costo de ordenar, permitiendo controlar los principales grupos de *ítems* que se pueden ordenar en un mismo momento, donde los productos se consumen simultáneamente, pero caen en periodos de revisión completamente diferentes. Este modelo desarrollado por *Atkins y Iyogun* permite encontrar las cantidades necesarias y los periodos de revisión adecuados a los productos [6].

El procedimiento de *Atkins e Iyogun* esencialmente asigna el mayor costo de reposición en pequeñas cantidades a los productos que se producen o compran con mayor frecuencia, manteniendo el tiempo esperado para la próxima reposición de estos productos en equilibrio [2].

Para el desarrollo de este algoritmo inicialmente se calcula el *EOQ*, usando la siguiente formula:

$$EOQ_i = \sqrt{\frac{2a_i D_i}{rv_i}} \tag{10}$$

donde:

$$a_i = costo\ menor\ de\ agregar\ un\ producto\ i$$

$$D_i = demanda\ anual\ del\ producto\ i$$

$$v_i = costo\ unitario\ del\ producto\ i$$

Al mismo tiempo, se calcula el suministro de tiempo equivalente para cada producto usando solo el menor costo de configuración a_i, asumiendo un año como 50 semanas.

$$T_i = \frac{EOQ_i(50)}{D_i}\ en\ semanas \tag{11}$$

Con esto, se obtiene un suministro de tiempo T_i para cada *ítem* dentro de una familia de productos, luego se elige el producto con el suministro de tiempo más pequeño y se

denota producto 1. Una pequeña porción $\propto_1$ del costo mayor A, se asigna a este producto. La idea es asignar eventualmente todo el costo mayor principal a varios productos de la familia. Si todo el costo estuviera distribuido en un solo producto, su *EOQ* podría incrementarse significativamente, lo mismo que su suministro de tiempo [2].

Asignar más y más $\propto_1$ al primer producto aumenta su suministro de tiempo, eventualmente hasta el punto de que coincide con el suministro de tiempo del segundo producto comprado con mayor frecuencia. Ahora asigne más del costo de instalación o reabastecimiento principal al primer producto, y algunos al producto 2, manteniendo los suministros de tiempo en equilibrio. Cuando estos dos suministros de tiempo igual aumentan al suministro de tiempo del tercer producto comprado con mayor frecuencia, comience a asignar $\propto_3$ a este tercer producto. Este proceso continúa hasta que se asigna toda la configuración principal, es decir $\sum_i \propto_i = 1$. Por lo tanto, cada vez que se ordena una familia, se contabiliza el costo total de la configuración [2].

Si se expresa el costo total para un *ítem* como $(\alpha_i A + a_i)$, es fácil resolver para un tiempo de suministro dado por:

$$\alpha_i = \frac{T_i^2 r_i v_i D_i}{2A} - \frac{a_i}{A}$$

donde:

$$A = costo\ de\ configuración\ por\ ordenar$$

3 Metodología

Para dar solución al problema de la empresa en estudio, se formula la siguiente metodología para la gestión de inventarios, la cual consta de cinco etapas para su ejecución.

1) *Identificación del sistema:* Esta identificación del sistema corresponde a la periodicidad o frecuencia con la que se realicen los inventarios en la empresa.
2) *Clasificación ABC:* Es aplicar el método de Pareto, el cual consiste en la clasificación de productos con base en su importancia para las ventas de la empresa y la cantidad de productos que estos representan para ellas. Importancia conocida como el 80% de las ventas están representadas por el 20% de los productos que se encuentran en almacén.
3) *Determinación de la demanda:* Se deben considerar los patrones de demanda: estacionaria, estacional, con tendencia o cíclica y tener en cuenta la variabilidad de la demanda.
4) *Evaluación y selección de sistemas de pronósticos:* Para calcular las demandas futuras con base en el comportamiento de la demanda de los productos, para este caso de estudio se evaluaron los modelos clásicos de pronósticos y los modelos ARIMA, resultando los modelos ARIMA con el menor error de pronóstico. Con estos modelos ARIMA se calculan los pronósticos de las demandas que serán utilizadas para aplicar la política de inventario.
5) *Evaluación y selección del sistema de control de inventarios:* En este trabajo, nos centramos en un grupo de sistemas que serán sistemas probabilísticos de

gestión de inventario, esto es, la demanda no es conocida con certeza. Las políticas seleccionadas serán la política (s, S) y la política (R, S).

6) *Sistema de abastecimiento conjunto*: En este punto se busca un equilibrio entre las decisiones de frecuencia de revisión del inventario y las cantidades a ordenar; logrando una coordinación de todos los productos, considerando que las ordenes se hacen a un solo proveedor. El sistema de revisión periódica será el algoritmo sugerido por *Atkins y Iyogun*.

4 Caso de estudio y resultados

La empresa en estudio es una empresa de origen mexicano, fundada en 1982. Comercializadora de partes de repuesto de suspensión y dirección para un mercado de autopartes. La empresa tiene renombre a nivel nacional como proveedora de refacciones al mercado automotriz, manejando alrededor de 1,000 *SKU´s* (*Stock Keeping Units*). Actualmente la empresa no cuenta con una herramienta de gestión eficiente en costos que le permita evaluar y controlar el sistema de inventarios de repuestos, como es de esperarse, se tienen bajos niveles de servicio por falta de material y un almacén con exceso de componentes y producto terminado.

La ejecución de la metodología para la gestión de inventarios es la siguiente:

1) *Identificación del sistema:* La empresa en estudio no cuenta con un sistema específico, por esta razón, como parte de la propuesta, se propone un adecuado sistema de gestión de inventarios para los productos seleccionados.

2) *Clasificación ABC:* Para la empresa en estudio se aplicó el principio de Pareto para establecer el grado de importancia de cada artículo. Con la aplicación de este principio de obtuvieron 160 artículos A de los 1,000 artículos en total. Los 15 artículos seleccionados para esta propuesta pertenecen a la clasificación A y son los que requieren mayor control, de acuerdo con información proporcionada por personal de la empresa.

3) *Determinación de la demanda:* Del análisis realizado a los artículos de clasificación A, se concluyó que presentan demanda con tendencia y, para algunos *ítems* la demanda es estacionaria, en general la demanda presenta variabilidad para los artículos A. Los 15 artículos seleccionados presentan tendencia, además de presentar variabilidad y solo uno presenta demanda estacionaria.

4) *Evaluación y selección de sistemas de pronósticos:* Para determinar los pronósticos de demanda de la empresa en estudio, se utilizaron los métodos de pronósticos cuantitativos clásicos y los modelos ARIMA, donde los modelos ARIMA presentaron el menor error porcentual absoluto medio, por lo que se utilizaron estos métodos de pronósticos para el cálculo de la demanda futura.

5) *Evaluación y selección del sistema de control de inventarios:* En esta etapa se considera un sistema de abastecimiento conjunto el cual busca un equilibrio entre las decisiones de frecuencia de revisión del inventario y las cantidades a ordenar, tomando en cuenta los datos obtenidos del caso de estudio. Un sistema de abastecimiento conjunto que se adapta a las necesidades y condiciones de la empresa, por ello se aplica un sistema de revisión periódica sugerido por *Atkins y Iyogun*.

En la Tabla I, se muestran los datos para 15 productos de la empresa de partes de repuesto, los pronósticos de la demanda se obtuvieron previamente, mediante modelos de pronósticos ARIMA, cuyos modelos arrojaron los menores errores de pronósticos comparados con los métodos de pronósticos clásicos, estos datos de demanda son utilizados para la selección de la política de inventario óptima *(s, S)* o *(R, S)*. Los datos adicionales son proporcionados por la empresa en estudios.

TABLA I. DATOS PARA 15 PRODUCTOS PRINCIPALES.

Datos	**Productos**														
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
d (unidades / mes)	392	777	460	172	279	189	321	270	210	149	110	189	202	258	210
σ (unidades)	105	163	96	55	58	70	89	81	59	60	33	45	50	72	38
L (mes)	3														
v ($ / unidad)	2.65	3.72	3.05	3.73	3.06	1.77	4.77	5.7	3.65	6.79	7.8	3.74	3.98	3.14	3.17
A ($ / pedido)	65														
r ($ / $ / año)	20%														
P_2	95%														
B_2	0.52	0.55	0.48	0.56	0.25	0.31	0.56	0.7	0.87	0.53	0.91	0.55	0.42	0.52	0.53
Se permiten *faltantes*.															

Fuente: Elaboración propia con información proporcionada por personal de la empresa.

TABLA II. COMPARACION DE POLITICAS DE INVENTARIO.

Item	**Política inventario (piezas)**		**Stock seguridad SS (piezas)**	**Costo Total Relevante TRC (DLS)**	**Diferencia costos (DLS)**
1	Continua **(s, S)**	(1676, 2933)	53	$ 921.36	$ 63.22
	Periódica **(R, S)**	(2, 2851)	134	$ 992.79	
2	Continua **(s, S)**	(2760, 4104)	144	$ 2,010.61	$ 72.51
	Periódica **(R, S)**	(2, 4538)	190	$ 2,062.94	
3	Continua **(s, S)**	(1461, 2569)	29	$ 1,082.92	$ 50.37
	Periódica **(R, S)**	(2, 2501)	97	$ 1,133.59	
4	Continua **(s, S)**	(822, 1923)	0	$ 384.00	$ 122.44
	Periódica **(R, S)**	(2, 1442)	77	$ 546.28	
5	Continua **(s, S)**	(834, 1678)	0	$ 642.32	$ 82.24
	Periódica **(R, S)**	(2, 1454)	59	$ 724.53	
6	Continua **(s, S)**	(535, 1135)	19	$ 676.47	$ 123.46
	Periódica **(R, S)**	(2, 949)	89	$ 799.93	
7	Continua **(s, S)**	(993, 1593)	30	$ 1,233.59	$ 113.81
	Periódica **(R, S)**	(2,1749)	144	$ 1,347.4	
8	Continua **(s, S)**	(837, 1437)	27	$ 1,369.71	$ 123.13
	Periódica **(R, S)**	(2, 1481)	131	$ 1,492.84	
9	Continua **(s, S)**	(650, 1250)	20	$ 903.31	$ 109.44
	Periódica **(R, S)**	(2, 1145)	95	$ 1,012.75	
10	Continua **(s, S)**	(467, 1067)	20	$ 910.37	$ 134.88
	Periódica **(R, S)**	(2, 842)	97	$ 1,045.25	
11	Continua **(s, S)**	(341, 941)	11	$ 1,002.80	$ 110.15
	Periódica **(R, S)**	(2, 604)	54	$ 1,112.95	
12	Continua **(s, S)**	(582, 1182)	15	$ 890.21	$103.07
	Periódica **(R, S)**	(2, 1018)	73	$ 993.28	
13	Continua **(s, S)**	(623, 1223)	17	$ 716.53	$ 100.94
	Periódica **(R, S)**	(2, 1091)	81	$ 817.47	
14	Continua **(s, S)**	(798, 1398)	24	$ 770.39	$ 107.19
	Periódica **(R, S)**	(2, 1406)	116	$ 877.58	
15	Continua **(s, S)**	(643, 1243)	13	$ 675.36	$ 98.26
	Periódica **(R, S)**	(2, 1112)	62	$ 773.62	

Fuente: Elaboración propia con información proporcionada por personal de la empresa.

Aplicando las fórmulas para las políticas de inventario propuestas para la empresa en estudio, se obtuvieron los resultados que se presentan en la Tabla II.

Estos resultados de las políticas de inventario nos indican claramente, que la mejor política de inventario para aplicar a la empresa es la política de revisión continua, ya que nos ahorraría $1,515.11 (DLS) anuales para estos 15 artículos estudiados.

Siguiendo con la política de revisión periódica y aplicando el algoritmo de *Atkins y Iyogun* para un reabastecimiento en conjunto, se obtienen los resultados mostrados en la Tabla III:

TABLA III. CALCULOS *EOQ* Y *T*.

Item	Demanda (piezas)	v (DLS)	*EOQ* (piezas)	*T* (semanas)
1	5964	2.65	300	2.52
2	11280	3.72	348	1.54
3	6672	3.05	296	2.22
4	2724	3.73	171	3.14
5	4044	3.06	230	2.84
6	3108	1.77	265	4.26
7	4920	4.77	203	2.06
8	4212	5.7	172	2.04
9	3228	3.65	188	2.91
10	2508	6.79	122	2.42
11	1716	7.8	94	2.73
12	2808	3.74	173	3.09
13	3024	3.98	174	2.88
14	3960	3.14	225	2.84
15	2976	3.17	194	3.26

Fuente: Elaboración propia con información proporcionada por personal de la empresa.

Siguiendo con el algoritmo de *Atkins y Iyogun* se calculan los α_i para cada producto, y se obtienen los nuevos periodos y EOQ para cada producto.

TABLA IV. VALORES OBTENIDOS USANDO ATKINS E IYOGUN.

Item	α_i	*T* (semanas)	Redondeo de *T*	*EOQ* (piezas)
1	0.066	3.276	4	478
2	0.216	3.276	4	903
3	0.091	3.276	4	534
4	0.026	3.276	4	218
5	0.063	3.276	4	324
6	0	3.276	4	249
7	0.121	3.276	4	394
8	0.139	3.276	4	337
9	0.041	3.276	4	259
10	0.07	3.276	4	201
11	0.04	3.276	4	138
12	0.012	3.276	4	225
13	0.024	3.276	4	242
14	0.064	3.276	4	317
15	0.027	3.276	4	239

Fuente: Elaboración propia con información proporcionada por personal de la empresa.

Estos nuevos periodos de revisión y *EOQ*, son los que mejor se ajustan a la empresa para generar ahorros en costos por abastecimiento en conjunto.

5 Discusiones y conclusiones

La industria de partes automotrices presenta cierta complejidad debido a las particularidades de sus productos en cuanto a variabilidad en la demanda e importancia de políticas que mantengan altos estándares de calidad. Los pronósticos son una herramienta poderosa que hace frente a este tipo de dificultades y a los cambios previstos en un futuro, contribuyendo así a la generación de beneficios económicos para las empresas.

A través de la elaboración de pronósticos de la demanda de productos, se puede desarrollar políticas de inventario adecuadas que minimicen su costo, tomando en cuenta el nivel de servicio ofrecido por la empresa. Los modelos de inventario utilizados se clasifican con base a los supuestos de demanda, periodo de revisión, faltantes, costos y tiempo de entrega (*lead time*). Adicionalmente, es importante mencionar que todos los modelos buscan optimizar sus políticas de reabastecimiento a través de la minimización de sus costos totales, los cuales en la mayoría de los modelos se utiliza un costo fijo de pedido, un costo de mantenimiento de inventario y costos por faltantes.

Con respecto a las políticas de inventario utilizadas, se recomienda priorizar los métodos probabilísticos ya que en sí la demanda para los productos de esta empresa siempre tiende a ser variable. Adicionalmente a esto una buena coordinación de productos, reducirán los costos por reabastecimiento como se observa en el caso de estudio para las empresas de piezas de repuesto automotrices.

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Modelo de simulación de la gestión de un *Job Shop*. Una herramienta de soporte a la toma de decisiones

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Resumen. La gestión de los sistemas de producción configurados como *Job Shop* implica toma de decisiones en ambientes de incertidumbre relacionada con: tiempos entre pedidos, tipo de producto, cantidad pedida, tiempos de operación, múltiples rutas de producción y tiempos de operación altamente variables. A pesar de este gran desafío, no hay mucho enfoque en el desarrollo de mejores soluciones para la gestión de la producción de alta variedad, probablemente porque los *Job Shop* que son pequeños en tamaño e ingresos, no han atraído la atención de los gurús de la gestión. La simulación es un enfoque de apoyo a la gestión que ha mostrado buenos resultados en razón a que puede lidiar muy bien con la incertidumbre. Es por esto que en esta ponencia se quiere mostrar un modelo de simulación para dar soporte a dicha gestión. Inicialmente se aborda el tema de la complejidad en la gestión del *Job Shop*, seguidamente se plantea la conveniencia de emplear simulación y las bases conceptuales requisito de un posible modelo. Al final, se expone el modelo desarrollado y se hace una corrida con un *Job Shop* hipotético, planteando 2 escenarios, en cuya comparación se emplean diferentes medidas de desempeño relacionadas con la eficiencia y la efectividad.

Keywords: Job Shop, Toma de Decisiones, Simulacion.

1 Introduccion

1.1 Definiendo un *Job Shop*

No es fácil encontrar una definición universalmente aceptada de una configuración de producción del tipo *Job Shop*. Sin embargo, muchas definiciones existentes cubren algunas características importantes de estas [1, 2]. La mayoría de las instalaciones de fabricación descritas como *Job Shop* son relativamente pequeñas en tamaño e ingresos y aceptan una variedad de pedidos personalizados en pequeñas cantidades. Un *Job Shop* es más general que una línea de producción que puede fabricar una variedad de productos uno tras otro de forma secuencial.

Específicamente, los *Job Shop* [3] incluyen muchos tipos de unidades de producción como talleres de máquinas, talleres de fabricación, talleres de forja, talleres de moldes,

talleres de herramientas y matrices, unidades personalizadas de trabajo de madera, fabricantes de muebles, talleres de reparación, laboratorios, ciertas unidades de servicio, etc. El volumen de producción personalizada ha ido aumentando a lo largo de los años junto con el nivel de automatización en las industrias. Dado que la producción en masa se está subcontratando, el porcentaje de unidades de producción de alta variedad está aumentando en los países occidentales y la metodología para mejorar la gestión de la producción de alta variedad en los talleres de trabajo es cada vez más relevante.

1.2 Complejidad inherente a la gestión de un *Job Shop*

En [3] se considera que muchos *Job Shop* pequeños y medianos se ocupan principalmente de una variedad numerosa de pedidos de pequeños volúmenes sin ninguna previsibilidad de los requisitos del proceso y los tiempos de llegada de los pedidos. Este fenómeno que involucra una demanda incierta y cambios impredecibles en la mezcla de productos en la planta de producción generalmente obliga a fabricar productos solo contra pedidos realizados por los clientes. La variación en la combinación de productos puede provocar fluctuaciones rápidas en los requisitos de materiales y recursos, y las pequeñas empresas no pueden permitirse mantener inventarios de una variedad amplia de materias primas para respaldar la producción sobre pedido. Por varias razones, los *Job Shop* tienden a utilizar máquinas multifuncionales y trabajadores con múltiples habilidades de capacidad limitada para procesar los pedidos de los clientes.

Muchos expertos en fabricación sugieren la simplificación del sistema para eliminar la complejidad de la producción de gran variedad. Sin embargo, la simplificación del sistema no siempre es sencilla, fácil o económica en la práctica, especialmente para talleres pequeños. Sin la simplificación del sistema, la gestión de una producción compleja y de gran variedad es bastante difícil. La simplificación del sistema sugerida por [4, 5] la manufactura esbelta (*lean manufacturing*) y la teoría de restricciones (TOC) aún no se implementa ampliamente en sistemas de producción tipo *Job Shop*. Estas metodologías parecen carecer de algo que es esencial para una gestión eficiente de la producción en muchos *Job Shop* pequeños y medianos.

Uno de los objetivos en la gestión del *Job Shop* es maximizar primero el desempeño general del sistema (taller) mediante el uso óptimo de las capacidades de recursos disponibles y luego identificar simplificaciones rentables, así como oportunidades de mejoras que pueden producir las mayores ganancias marginales en los KPI. Un enfoque mediante el empleo de simulación puede ayudar a evaluar tanto el desempeño general del sistema, así como posibilidades de mejoramiento del mismo.

1.3 Simulación

Para [6] la simulación está referida a técnicas que, usando computadores, imitan o *simulan* la operación de varias clases de instalaciones y procesos del mundo real. En otras palabras, computadores que pueden fingir digitalmente ser una fábrica, un avión o un mercado de abarrotes. La instalación o proceso de interés usualmente es llamado sistema, y en pro de estudiarlo científicamente, a menudo se establecen un conjunto de

suposiciones de cómo opera. Estas suposiciones usualmente toman la forma de relaciones matemáticas y lógicas constituyendo lo que se denomina un *modelo* que es usado para intentar obtener algún entendimiento sobre cómo el correspondiente sistema se comporta a través del tiempo. Para [7], al imitar la operación de un sistema real, la simulación genera una historia artificial del sistema y su observación permite inferir lo concerniente a las características de operación del sistema real. Según [8] la simulación es el proceso de diseñar y desarrollar un modelo de un sistema o proceso real y conducir experimentos con el propósito de entender el comportamiento del sistema o evaluar varias estrategias (dentro de límites impuestos por un criterio o conjunto de criterios) para su operación.

Si las relaciones que componen el modelo son bastante simples, es posible usar una solución analítica (métodos matemáticos tales como algebra, calculo o teoría de probabilidad) para obtener información exacta sobre las preguntas de interés. En casi todas las soluciones analíticas, la meta es determinar soluciones óptimas. No obstante, muchos sistemas del mundo real (por ejemplo, los sistemas de producción tipo *Job Shop*) son demasiado complejos para modelarlos y evaluarlos analíticamente. Un modelo de simulación comúnmente toma la forma de hipótesis acerca del funcionamiento de un sistema, expresadas como relaciones matemáticas o lógicas entre las entidades de interés del sistema.

En [9] se plantea que, en contraste con las soluciones analíticas, el proceso de simulación incluye la ejecución del modelo a través del tiempo en una computadora, para producir muestras representativas de las mediciones del desempeño del sistema. Desde este punto de vista, se puede considerar la simulación como un experimento de muestreo sobre el comportamiento en el tiempo, del sistema real, cuyos resultados son puntos de muestra. Es claro que mientras más puntos de muestra se generen, mejor será la estimación sobre el desempeño del sistema.

Específicamente la simulación por eventos discretos (DES) se centra en representar sistemas en los que es necesario realizar una secuencia de operaciones o tareas y sus eventos asociados. Esto significa que podemos pensar en estas operaciones como un proceso e ilustrarlas con un diagrama de flujo. En DES, el estudio con simulación permite analizar las “cosas” (trabajos) que pasan por el proceso y los recursos que les ayudan a completar su flujo.

Para [10], las características de la simulación, que hacen que sea una potente herramienta de planificación y toma de decisiones, se pueden resumir en:

- Captura las interdependencias de un sistema.
- Representa la variabilidad del Sistema.
- Versatilidad para modelar casi cualquier sistema.
- Expone el comportamiento sobre el tiempo.
- Es de menor costo y consumo de tiempo simular que experimentar con el sistema real.

- Provee información sobre múltiples medidas de desempeño (KPI).
- Es visualmente atractivo e involucra el interés de los usuarios del sistema.
- Provee resultados que son fáciles de entender y comunicar.
- Provee compresión espacio-temporal.
- Fuerza al analista a pensar en los detalles operativos del sistema.

Definido lo que es un sistema de producción configurado en *Job Shop* y la complejidad asociada a su gestión y previamente haber caracterizado la simulación como herramienta apropiada de soporte en la toma de decisiones bajo incertidumbre, se identifican a continuación los requisitos que debe satisfacer el modelo mencionado en el título.

2 Aproximación conceptual al modelo de simulación de un *Job Shop*

En esta sección se planteará conceptualmente la funcionalidad del modelo que posteriormente se codificará en un software de simulación del tipo DES.

2.1 Requisitos funcionales mínimos que debe satisfacer el modelo

Al revisar la literatura [3, 9] sobre el funcionamiento de un sistema configurado en *Job Shop* se encuentran las siguientes características, tanto de componentes estructurales como operacionales:

1. Se recibe en momentos inciertos pedidos (trabajos) de una amplia variedad de productos en pequeñas cantidades con requisitos impredecibles de proceso.
2. Los productos pueden tener variaciones en cantidades, requisitos de materiales, rutas, prioridades, plazo de entrega y márgenes.
3. Un pedido puede implicar la producción de un conjunto de componentes similares o la producción de diferentes tipos de componentes y la fabricación de subconjuntos y un ensamblaje final a partir de esos componentes.
4. Varios pedidos pueden moverse simultáneamente a través del sistema a lo largo de las respectivas rutas mientras compiten por recursos compartidos.
5. El procesamiento de un pedido puede incluir algunas operaciones externas.
6. Las operaciones de fabricación de un pedido pueden ser secuenciales o pueden tener ciertas relaciones de precedencia.
7. El conjunto de operaciones y relaciones de precedencia puede variar según el producto.
8. Los tiempos de alistamiento y de proceso de cualquier operación pueden variar según el trabajo.
9. Los tiempos de alistamiento para las operaciones también pueden depender de la secuencia del trabajo

10. Una operación puede requerir un solo recurso o puede requerir simultáneamente múltiples recursos como máquinas, trabajadores, etc. La duración misma de la operación puede ser variable.
11. Los recursos pueden ser máquinas multifuncionales y trabajadores polivalentes.
12. Los recursos pueden tener calendarios individuales (horas de trabajo) y excepciones de calendario.
13. Una operación larga puede o no ser compartida por varios recursos alternativos para reducir su duración.
14. El material de un trabajo puede moverse a través del sistema como un solo lote o como pequeños lotes de transferencia.
15. Las máquinas y operarios se agrupan por proceso

2.2 Conceptualización de los componentes estructurales del sistema

Al revisar la lista anterior de requisitos funcionales encontramos que este tipo de sistemas tiene las siguientes características estructurales:

Distribución en planta: Según los requisitos funcionales 11 y 15, las necesidades espaciales pueden considerar desde cientos a miles de m2 de área que incluya además de los espacios de maquinado, espacios (vías) para el flujo de materiales, personas y equipo de transporte.

Máquinas, operarios y/o equipo de transporte: Los requisitos funcionales 3, 14 y 15 indican que el modelo debe ser capaz de representar estos componentes estructurales, tanto espacial como operacionalmente. Espacialmente mediante coordenadas tipo plano cartesiano. Operacionalmente en términos de tiempos de proceso, alistamiento, entre fallos, etc.

Materia prima, producto en proceso y producto terminado: Los requisitos funcionales 2, 3 y 14 implican que el modelo debe ser capaz de representar los 3 estados: el pedido (producto), la materia prima y el producto en proceso.

2.3 Conceptualización de los componentes operacionales del sistema

De la lista de requisitos funcionales anterior encontramos que el modelo a desarrollar debe ser capaz de representar el siguiente comportamiento operativo del sistema:

Pedidos de clientes: Según el requisito funcional 1 se debe modelar tiempos entre pedidos, tipo de producto y cantidad pedida de forma aleatoria (muestreados estos valores desde distribuciones de probabilidad).

Secuencia de fabricación de productos: Según los requisitos funcionales 2, 4, 6 y 7 se debe poder representar una ruta de procesamiento (secuencia de operaciones) para cada tipo de producto. Si se consideran m máquinas y n trabajos, una posible secuencia

de operaciones por producto se ilustra en la Fig. 1, la cual representa una configuración *Job Shop* para m=6 máquinas y n=15 productos.

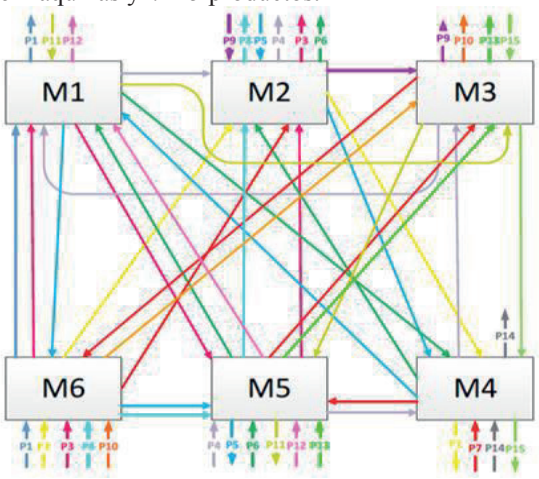

Fig. 1. Secuencia de procesamiento de 15 productos en 6 máquinas.

Tiempos de alistamiento de máquinas: Según los requisitos funcionales 8 y 9, los tiempos de alistamiento pueden depender de la secuencia de procesamiento (ver Fig. 1) y/o del tipo de producto a fabricar.

Tiempos de procesamiento de máquinas: Según el requisito funcional 8 el tiempo de proceso en cada máquina depende del tipo de producto. Además, el requisito funcional 10 establece que el tiempo de procesamiento en cada máquina no necesariamente es constante.

Uso de operarios en los procesos: Los requisitos funcionales 10, 11 y 12 indican que en el modelo debería poder representarse el trabajo de operarios, ya sea en labores de procesamiento como de manejo de materiales (su transporte).

2.4 Requisitos mínimos de entrada de parámetros que debe satisfacer el modelo

En razón a que el modelo será usado por personas (tomadores de decisiones) que no necesariamente son expertos en simulación, se hace indispensable que este tenga una interfaz usuario-modelo simple y apta para poder parametrizar la operación del mismo. Por tanto, debe cumplir con los siguientes requisitos de uso, al permitir el ingreso (algunos en formato tabular) de los siguientes parámetros de operación del sistema a simular:

1. Probabilidad (en %) de pedido de un determinado producto.
2. Cantidades mínima y máxima por tipo de producto que los clientes piden.
3. Tiempo de proceso de cada producto en cada máquina según distribución de probabilidad teórica o empírica.

4. Tiempo de alistamiento (si aplica) de cada producto en cada máquina según distribución de probabilidad teórica o empírica.
5. Ruta de procesamiento por cada tipo de producto acorde a lo ilustrado en la Fig. 1.

2.5 Requisitos mínimos de información de salida que debe satisfacer el modelo

Esta información debe proporcionarse en términos de KPI (*Key Performance Indicators*) de interés en la toma de decisiones relacionadas con la gestión de un *Job Shop*. Para un Job Shop se sugieren los siguientes KPI:

1. Relacionados con la eficiencia (uso de los recursos productivos):
    - Tasas de utlizacion de maquinas
    - Tasas de utilizacion de operarios

2. Relacionados con la efectividad (logro de los resultados):
    - Pedidos colocados y fabricados en un periodo de tiempo.
    - Productos pedidos y fabricados en un periodo tiempo.
    - Tiempos mínimos, promedio y máximo de fabricación por pedido.
    - Tiempos mínimos, promedio y máximo de fabricación de pedidos por tipo de producto.
    - Niveles de WIP.

Identificado a nivel conceptual el funcionamiento que debe tener el modelo de simulación de un sistema de producción configurado en *Job Shop* para soportar la toma de decisiones, se procede a codificar el modelo en un software de simulación tipo DES. A continuación, se expone el modelo desarrollado.

3 Resultado: Modelo de Simulación

El modelo se desarrolló en el software FlexSim v.2020. Para efectos de demostración se describe a continuación el modelo con aplicación a un sistema *Job Shop* configurado con $m = 3$ máquinas y $n = 3$ productos.

3.1 Modelamiento de la secuencia de procesamiento por producto, distribución en planta y operarios

En la Fig. 2 se muestra la secuencia de procesamiento que sigue cada producto a través de las maquinas M1, M2 y M3. Donde CM1, CM2 y CM3 son las respectivas colas de espera de la disponibilidad de cada máquina. Así, las secuencias son:

Producto A: CM1►M1►CM3►M3►CM2►M2
Producto B: CM3►M3►CM1►M1►CM2►M2

Producto C: CM2►M2►CM3►M3►CM1►M1

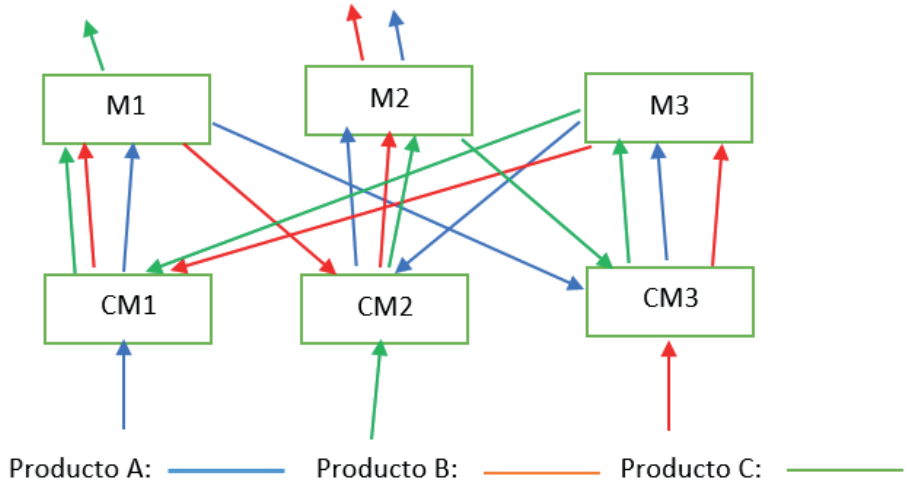

Fig. 2. Secuencia de procesamiento de 3 productos en 3 máquinas.

Para introducir una secuencia de fabricación especifica al modelo, el usuario digita esta secuencia de manera textual en una tabla en Excel, la cual es leída desde el modelo al momento de iniciar la simulación. La Fig. 3 muestra los datos correspondientes a la secuencia mostrada en la Fig. 2: secuencia de procesamiento 1. Igualmente es posible modelar otra secuencia según se muestra en la secuencia de procesamiento 2, en la cual los productos A y B son de nuevo procesados por la M1.

Secuencia procesamiento 1

	ProductoA	ProductoB	ProductoC
Espera1	CM1	CM3	CM2
Operacion1	M1	M3	M2
Espera2	CM3	CM1	CM3
Operacion2	M3	M1	M3
Espera3	CM2	CM2	CM2
Operacion3	M2	M2	M2
Espera4	Bodega	Bodega	Bodega
Operacion4			
Espera5			

Secuencia procesamiento 2

	ProductoA	ProductoB	ProductoC
Espera1	CM1	CM3	CM2
Operacion1	M1	M3	M2
Espera2	CM3	CM1	CM3
Operacion2	M3	M1	M3
Espera3	CM2	CM2	CM2
Operacion3	M2	M2	M2
Espera4	CM1	CM1	Bodega
Operacion4	M1	M1	
Espera5	Bodega	Bodega	

Fig. 3. Dos secuencias de procesamiento de 3 productos en 3 máquinas.

En la Fig. 4, se muestra una representación gráfica de la distribución en planta, la cual es un espacio rectangular (ver cuadricula) de área 24 m x 18 m (432 m2). Además de las máquinas y sus colas de espera, se incluye un punto de arribo de los pedidos, un operario por cada máquina para el transporte y procesamiento (las líneas curvas denotan las trayectorias de movimiento) de la materia prima y producto y una bodega para el almacenamiento de este último cuando esté terminado. Es conveniente resaltar que el modelo se simula con animación en 3D.

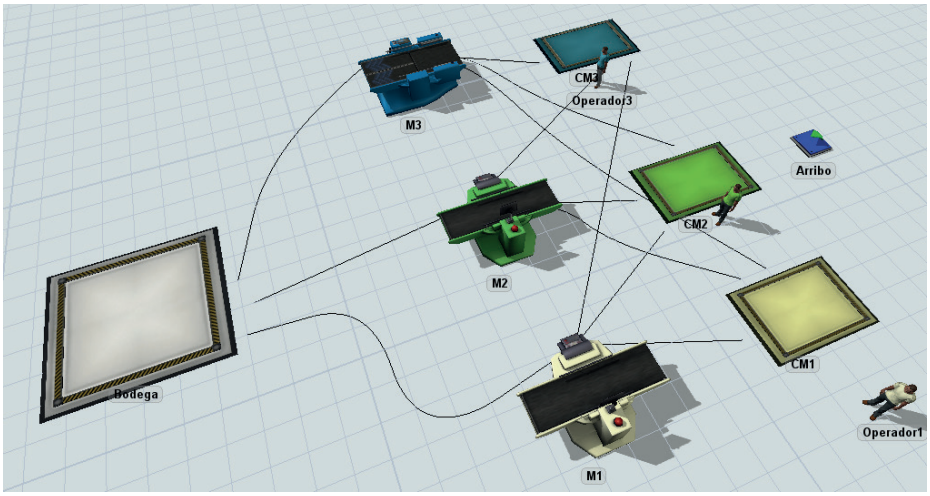

Fig. 4. Representación grafica del modelo de simulación.

En la Tabla 1 se muestra los parámetros de actuación de los operarios, los cuales son fijos, es decir el usuario del modelo no los puede cambiar. Los tiempos que emplean los operarios en las maquinas procesando los productos se describen más adelante.

Tabla 1. Parámetros fijos de operación de los operarios

Parametro	Valor
Velocidad de desplazamiento	25 m/s
Tiempo de cargue	6 s
Tiempo descargue	6 s
Capacidad de cargue	1 pedido a la vez
Descansos	Cada 2 horas 1 descanso de 10 minutos

3.2 Modelamiento de los pedidos

Se representan estos mediante 3 parámetros probabilísticos. El primero es el tiempo entre pedidos en horas, que se muestreara desde una distribución triangular. El segundo es la probabilidad que tiene cada producto de ser pedido y el tercero la cantidad pedida. En un ambiente real, estos tres parámetros se pueden estimar a partir de los datos históricos del sistema de información de pedidos. En la Fig. 5 se muestran valores específicos para los 2 últimos parámetros. Como se observa el primer parámetro se modela

con una distribución de probabilidad empírica y el segundo mediante una distribución uniforme para la cantidad pedida por tipo de producto.

Probabilidad de pedido por producto

	Probabilidad	Type
ProductoA	45	1
ProductoB	25	2
ProductoC	30	3

Cantidad a pedir por producto

	Minimo	Maximo
ProductoA	5	10
ProductoB	3	8
ProductoC	5	9

Fig. 5. Probabilidades de pedido por producto y cantidad pedida.

3.3 Modelamiento de los tiempos de proceso en las maquinas

El tiempo que demora el proceso en cada máquina se representa mediante valores probabilísticos muestreados desde distribuciones de probabilidad teóricas. El software *FlexSim* soporta más de 30 tipos de distribuciones de probabilidad. Para el caso de demostración se emplearán las distribuciones: uniforme, triangular y normal. Igualmente es posible representar tiempos de proceso constante como se muestra en la Fig. 6 (caso del tiempo de proceso del Producto B en M3).

	M1	M2	M3
ProductoA	return uniform(4,8,1);	return uniform(4,8,1);	return normal(3.5,0.4,1);
ProductoB	return uniform(5,9,2);	return triangular(2.2,7.5,6.1,3);	return 3.2;
Productoc	return triangular(2.2,6.5,4.1,3);	return uniform(4,8,1);	return normal(2.8,0.2,1);

Fig. 6. Tiempos de proceso (minutos) de cada producto en cada máquina.

3.4 Modelamiento de los tiempos de alistamiento de las maquinas

El tiempo que demora preparar cada máquina antes de manufacturar un producto determinado se representa mediante valores determinísticos. En la Fig. 7 se muestran los valores a emplear en la demostración. Igualmente es posible representar si una máquina no requiere tiempo de alistamiento para determinado producto, simplemente se representa con el valor 0.

	M1	M2	M3
ProductoA	return 30;	return 45;	return 30;
ProductoB	return 40;	return 0;	return 30;
Productoc	return 30;	return 30;	return 0;

Fig. 7. Tiempos de alistamiento (segundos) de cada producto en cada máquina.

4 Ejemplo de simulación del modelo

Se considerarán 2 escenarios de experimentación con el fin de mostrar las bondades del modelo en el apoyo a la toma de decisiones en la gestión de un sistema de producción configurado en *Job Shop*. Se muestra a continuación los resultados en términos de los KPI propuestos en la sección 2.5, simulando a una longitud de corrida de 192 horas (1 mes con jornadas de trabajo de 48 horas semana) y 10 réplicas.

4.1 Escenario 1: Simulación con parámetros de operación del sistema actual

Este escenario base de experimentación considerara tiempos entre pedidos de mínimo 0.33, máximo 0.75 y más frecuente 0.5 horas y empleara como otros parámetros de entrada los descritos en la sección 3.

KPI relacionados con la eficiencia: En las figuras 8 y 9 se muestran las tasas de utilización de máquinas y operarios.

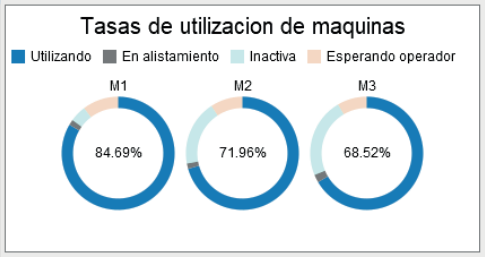

Fig. 8. Tasas de utilización de las maquinas: Escenario 1.

Se observa que la M1 es la de mayor utilización. En las M1 y M2 hay disponibilidad de utilización alrededor del 15%. En las 3 máquinas el tiempo de alistamiento es mínimo, pero el paro de las maquinas por descansos del operador puede llegar al 10%.

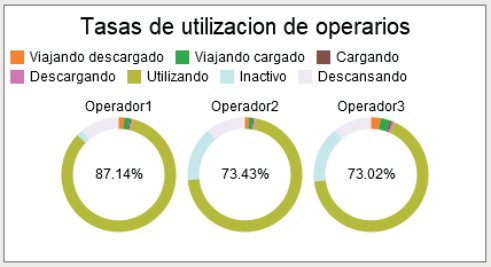

Fig. 9. Tasas de utilización de los operarios: Escenario 1.

Se observa que el Operador1 es el de mayor utilización. Los operadores 2 y 3 tienen disponibilidad de utilización adicional alrededor del 10%. Para los 3 operadores los tiempos de viaje, cargue y descargue son poco significativos.

KPI relacionados con la efectividad: En las figuras 10, 11, 12 y 13 se muestran los niveles de throughput, tiempo de proceso y WIP alcanzados.

Pedidos y cantidades de producto colocados	**Pedidos y cantidades de producto fabricados**
Numero de pedidos colocados x pdto **vPedidosA** 161 **vPedidosB** 88 **vPedidosC** 161	**Numero de pedidos fabricados x pdto** **vPedidosFabricadosA** 102 **vPedidosFabricadosB** 62 **vPedidosFabricadosC** 72
Cantidades pedidas x Pdto **vPedPdtoA** 1220 **vPedPdtoB** 476 **vPedPdtoC** 832	**Cantidades fabricadas x Pdto** **vFabPdtoA** 778 **vFabPdtoB** 338 **vFabPdtoC** 513

Fig. 10. Volumen de pedidos colocados y fabricados por producto (throughput): Escenario 1.

Se puede deducir de los resultados mostrados en la Figura 10 que el nivel de satisfacción de la demanda es muy bajo, sobre todos para los productos A y C (aproximadamente del 63% para A y 61% para C en un periodo de tiempo de 192 horas). La figura 11 muestra que a medida que el periodo de tiempo se extiende estos niveles de satisfacción de la demanda siguen bajando.

Los resultados desplegados en la figura 12 muestran que el tiempo promedio en el sistema de un pedido desde que se coloca hasta que se entrega esta alrededor de 12 horas, inclusive un pedido del producto A demoro alrededor de 66 horas (máximo = 3967 minutos). Llama la atención que en promedio un pedido de producto A demora 32 horas.

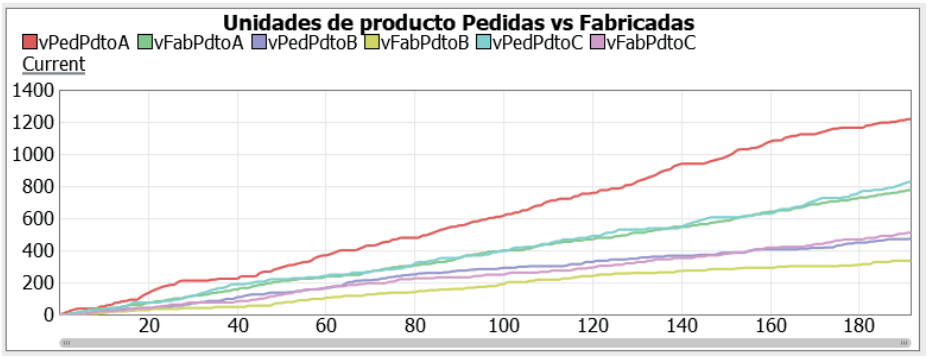

Fig. 11. Tendencia en el tiempo de productos pedidos vs fabricados: Escenario 1.

Tiempo de fabricación por pedido en minutos

Promedio	Minimo	Maximo
724.8	11.1	3967.0

Tiempo de fabricación por pedido/producto (Tipos 1, 2 y 3 corresponden con: A, B y C respectivamente)

Tiempo en el sistema pedidos por tipo de producto

Type	Promedio	Maximo	Minimo
1	1963.3	35.0	3967.0
2	63.0	11.1	231.1
3	105.5	18.5	284.7

Fig. 12. Tiempos de fabricación de pedidos: Escenario 1.

La Figura 13 muestra el estado del WIP en la planta de producción al terminar la simulación. Ha de connotarse el alto número de pedidos que quedan en proceso esperando ser procesados en M1 (122 esperando en CM1). Cada caja denota un pedido y su color el tipo de producto: rojo, verde y azul se corresponden con los tipos A, B y C.

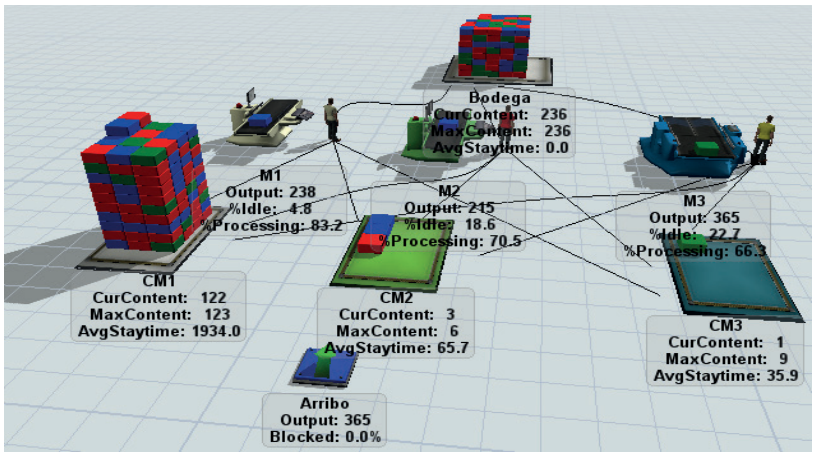

Fig. 13. Estado planta de producción al finalizar la simulación: Escenario 1.

4.2 Escenario 2: Simulación con parámetros de operación propuestos

Asumiendo el papel de un tomador de decisiones y en pro de mejorar los KPI de eficiencia y efectividad y considerando según el corto análisis hecho que la problemática se centra en la alta probabilidad de demanda de los productos A y C, además de su volumen de pedido (los piden el 75% de las veces en cantidades hasta de 10 unidades, ver Figura 5) se toma la decisión de emplear como tiempo de proceso un valor constante mínimo, bajo el supuesto que se emplearan máquinas automáticas y/o se mejorara el método de operación. En la Figura 14 se muestra el cambio propuesto. (Comparar con la Figura 6 para ver el cambio en los tiempos de operación).

	M1	M2	M3
ProductoA	return 4;	return 4;	return 3.5;
ProductoB	return uniform(5,9,2);	return triangular(2.2,7.5,6.1,3);	return 3.2;
Productoc	return 2.2;	return 4;	return 2.8;

Fig. 14. Nuevos tiempos de operación (minutos) de productos A y C en cada máquina.

KPI relacionados con la eficiencia: En la Figura 15 se muestran las nuevas tasas de utilización de máquinas y operarios. Se puede apreciar un aumento en la utilización de las máquinas M1 y M2, una disminución de M3 y aumento en la utilización del Operador3 y disminución en la utilización del Operador2.

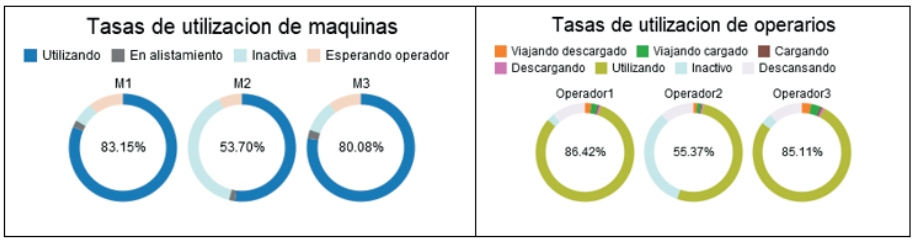

Fig. 15. Tasas de utilización de máquinas y operarios: Escenario 2.

KPI relacionados con la efectividad: En la Figura 16 se observa el throughput alcanzado en el escenario 2. Respecto al escenario 1, se pasó de 236 a 312 pedidos fabricados. Y de 1629 unidades de producto fabricadas en el escenario 1 a 2160 en el escenario 2.

Numero de pedidos fabricados x pdto		Cantidades fabricadas x Pdto	
vPedidosFabricadosA	144	vFabPdtoA	1095
vPedidosFabricadosB	81	vFabPdtoB	445
vPedidosFabricadosC	87	vFabPdtoC	620

Fig. 16. Volumen de pedidos/productos fabricados por producto (throughput): Escenario 2.

Los resultados desplegados en la Figura 17 muestran que el tiempo promedio en el sistema de un pedido desde que se coloca hasta que se entrega disminuyo de 12 a 6.4 horas. Y específicamente el tiempo de fabricación de un pedido de productos A paso de 32 a 13.2 horas.

Tiempo en el sistema pedidos en minutos

Promedio	Minimo	Maximo
382.7	12.6	1569.1

Tiempo en el sistema pedidos por tipo de producto

Type	Promedio	Minimo	Maximo
1	789.9	21.4	1569.1
2	118.9	18.4	247.3
3	33.2	12.6	75.8

Fig. 17. Tiempos de fabricación de pedidos: Escenario 2.

La Figura 18 muestra el estado del WIP en la planta de producción al terminar la simulación. Ha de connotarse que el número de pedidos que quedan esperando ser procesados en M1 paso de 122 en el escenario 1 a 47 en el escenario 2.

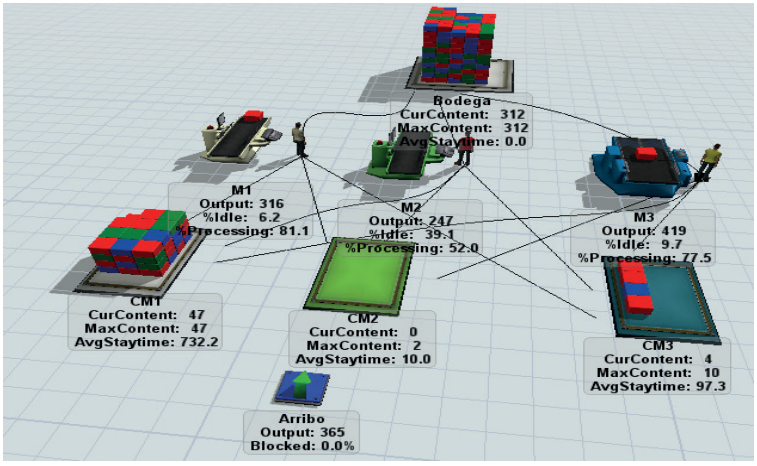

Fig. 18. Estado planta de producción al finalizar la simulación: Escenario 2.

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A strategic reference model for the competitiveness of the port supply chain

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Keywords: Port competitiveness · Port supply chain · Reference Model

The logistics services industry is a fundamental pillar for foreign trade and the economic and social development of nations. Foreign trade by sea represents 90% of volume and 70% in terms of the value of world trade, according to the United Nations Conference on Trade and Development (UNCTAD, 2018). Before the COVID-19 pandemic, the UNCTAD was estimating that international maritime trade would expand at an average annual growth rate of 3.5% over the 2019-2024 period. However, the pandemic COVID-19 caused a deceleration in all the economies. Now, in the recovery phase, global supply chains need to be more efficient than ever.

Ports act as an interface between ships and shore for cargo transferring, where the evolution of global supply chains and the recent disruptive events have imposed significant challenges to their role as functional nodes in logistics networks [1,2]. To cope with this challenge, ports must evolve and adapt their operations to reduce operational costs while increasing the service levels to their users.

Port competitiveness is related to the development of different innovative alternatives and strategies with which ports can compete, as well as the efficient implementation of these strategies to attract more users and cargo to the port [3,4,5]. This should ensure a satisfactory result to all the actors that participate in the port supply chain and, therefore, the port plays a double role.

On a national level perspective, the World Bank provides logistics and competitiveness indicators. The Logistics Performance Index (LPI) measures aspects related to the efficiency of ports, Customs and logistics services for 185 countries. If we observe the results obtained by the countries in Latin America and the Caribbean, it is possible to note a structural gap as the countries have not been able to reach better positions with respect to other countries such as Germany or the Netherlands, that are always in the first positions of the ranking. This highlights the importance of trade facilitation practices as well as the need of ports being more competitive by providing better service levels in the import and export processes.

In this research, we propose a Strategic Reference Model of Management and Competitiveness of the port supply chain that aims to provide port managers guidelines and best practices so as to facilitate the development of effective port transformation programs in institutional, operational, digital and innovation matters. For this, we consider

as a case study, a set of representative ports in the Region of Latin America and the Caribbean. The research follows a grounded theory approach, in which field work such as interviews and focus group activities, as well as a literature review, provided insights of what are the areas or dimensions of competitiveness resulting in six prioritized areas that organize best practices observed and validated by the industry at a global and regional level and that, by measuring their degree of implementation in the port systems of the region, provides a qualitative and quantitative basis for ports in the region be able to implement continuous improvement programs.

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Adaptation of the Balanced Scorecard to Latin American Higher Education Institutions in the Context of Strategic Management: A Systematic Review with Meta-analysis.

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Abstract. The objective of this research is to examine from a scientific perspective how the use of the Balanced Scorecard has been adapted in the various types of higher education institutions in Latin America within the context of their strategic management, through a systematic review with meta-analysis, in order to contribute to the development of strategic processes in these organizations, given the relevance they have acquired, based on the new state regulations and the speed of social and cultural changes in the region. To achieve this, a statistical analysis was carried out, first to identify the most frequent implementation techniques and the type of institution in which the studies were conducted; and, secondly, to examine the underlying interrelationships between the variables involved in the strategic context through the chi-squared test. The results showed a scarcity, but incipient evidence from the year 2000, of works mostly concentrated in universities of three countries, both in public and private organizations, with greater use of the original structure of Kaplan and Norton, and of the perspective "Customer". With the meta-analysis, no relationship was found between the ownership of the organization and, on the one hand, the structure of strategic dimensions used in the comprehensive scorecard and, secondly, with the perspectives used.

Keywords: Balanced Scorecard, Strategic Management, Latin American Higher Education Institutions, Systematic Review, Meta-analysis.

1 Introduction

In the same way that it has occurred in the most developed countries of the world, the industrial sector of higher education (HE) in Latin America is now going through a time of rapid and great changes, due in large part to the transition from an industrial society to the knowledge society [1]. Now higher education institutions (HEIs) must face greater competitiveness in their markets, more empowered students, universalization of education and a new legal and regulatory framework. There is a transition, with different nuances between countries, towards expansion and then towards quality[1],

[1] In another aspect of diagnosis there is also evidence of a transition from the elite to inclusion.

phenomena that developed countries began to experience at the beginning of the 20th century [2].

With regard to expansion, in most Latin American countries there is strong growth in access to HE and enrollment, especially in the lower socioeconomic strata [3], presenting a large variance, which depends on factors such as educational spending as a percentage of gross domestic product and the nation's budget, and on the Net Enrolment Rate in secondary education[2] [1].

Because the States are not able to satisfy all the need for SE, now this service is shared by public and private institutions [2], whose difference, according to international standards[3] [4], lies in whether it is public or private the entity that has the ultimate power to make decisions about the institution's affairs[4]. Worldwide, 33% of students are enrolled in private HEIs [5], and an accelerated growth of private HE [6] is reflected in a growing Gross Enrollment Rate[5] in Latin America [7], an area that has the highest participation worldwide, with 48% of its enrollment in private HEIs[6] [2]. At one end of the spectrum are countries such as Brazil, Chile, El Salvador, Peru and the Dominican Republic, concentrating their enrollment in the private sector, and at the other end Cuba, without private registration [8]. A reflection of the above is the decrease in public investment per student in Latin America [3].

On the other hand, the transition to quality has implied the establishment of new state policies, which tend to order and try to regulate an increasingly heterogeneous and complex market, which have resulted in changes at the legislative level, in the contribution of state funds, and in the creation of evaluating and supervising bodies [9]. Opposite examples of this reality are represented by Mexico, as a case of less regulation, and Chile, as an example of greater regulation.

Within this context are the accreditation and/or quality assurance systems[7], which oblige HEIs to carry out strategic processes, execute the minimum functions required by each State, carry out performance and quality evaluations based on standardized indicators, and accountability (delivery of information, compliance with standards, transparency) [10]. For example, in Chile, the HE law [11] establishes strategic management as one of the dimensions to be accredited, and also the obligation to carry out

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2 It is defined as the total number of students in the theoretical age group for the secondary level, enrolled at that level, expressed as a percentage of the total population in that age group [29].

3 Each country provides information on private and public HEIs to international organizations such as UNESCO [5] according to its own taxonomy. In addition, HEIs differ in terms of owner, mission, main source of income, student aid system, quality control system, institutional governance mode, and academic staff management system, with a different ideological-cultural meaning depending on the country [30].

4 Private institutions in turn are classified as "dependent" and "independent" of the government, which only refers to the degree of dependence of an institution on government financing [4].

5 In higher education, the Gross Enrolment Rate is defined as the total number of students enrolled in tertiary education, expressed as a percentage of the population in the five-year group immediately after secondary education, typically 18 to 22 years old [27].

6 In Europe in 2010 it was only 15% [31].

7 Almost every nation in the region now has an accrediting agency.

a process of institutional strategic planning, which generally it is documented in a strategic development plan.

One of the tools used by HEIs in their strategic processes is the Balanced Scorecard (BSC), which was presented by Kaplan and Norton 27 years ago [12], based on the integration and complementation of the literatures on quality, efficient management, financial economics, and stakeholder theory. It started as a tool to measure the performance of a company through financial and non-financial measures that promote the creation of long-term value for its shareholders, based on four perspectives: financial, customers, internal business, and innovation and learning ago [12]. Soon its authors realized that the priority in companies was to implement their strategy and that, therefore, the first thing was not to generate the metrics, but rather the logic is to describe the strategy through strategic objectives, based on the structure of the four perspectives, which finally leads to the selection of the ideal indicators [13]. Then, with the incorporation of the strategy map, the focus is taken away from the indicators, and put on the objectives and the relationship between them [14].

Starting in the mid-90s, the BSC began to be applied in both public institutions and non-profit organizations, so Kaplan and Norton generated an adaptation of the BSC to this type of organizations [14], which do not measure their performance with financial indicators, but through effectiveness to generate benefits to the recipients. As seen in **Fig. 1**, the financial perspective disappears from the first level, as it is not its main or final objective, being replaced by objectives related to its impact and mission; and the client perspective is broadened to donors, who provide financial resources (pay for the service), and to clients or beneficiaries, who are the recipients of the service[8].

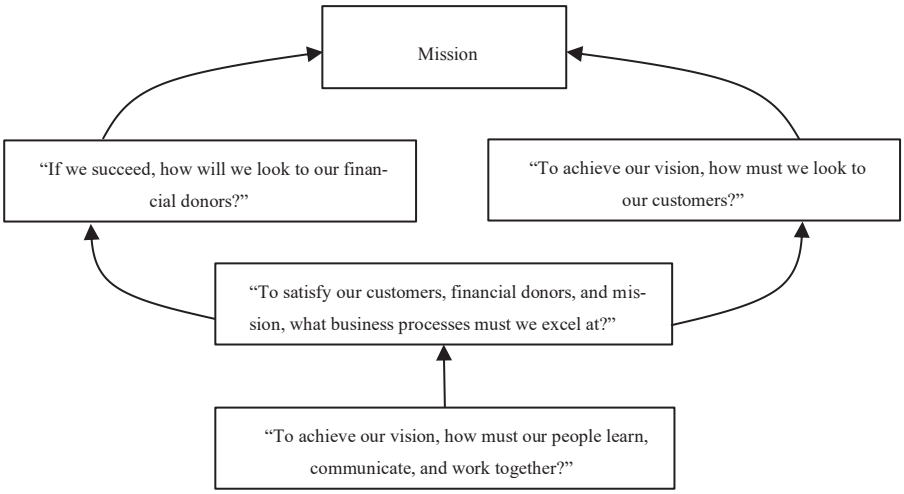

Fig. 1. Adaptation of the BSC to non-profit organizations (Source: Kaplan & Norton [14]).

[8] Faced with the question of who is the client, a cross-cutting problem for non-profit and public organizations, instead of opting for one or the other, in practice the perspectives of the donor and the recipient have been placed at the same level [14].

Then came the creation of the concept of Organization focused on strategy [14], based on 5 principles [15], and an enrichment of the methodology in 2004 [16], but it is the adaptation to other types of organizations in 2001, which should lead to a greater use of the BSC in ES.

A review of articles in ISI Web and Scopus [17] shows that in 2006 25% of the total studies found used the BSC in the context of strategic management, that only 3.8% of the total correspond to applications in educational institutions and no evidence of work was found in Latin America; there is little evidence on the application of the BSC in HEIs, compared to companies [18].

From the need to know how the BSC is being applied in HE, the idea of generating a systematic review[9] was born, whose advantage over a narrative review of the literature is that it reduces bias and error, allowing the generalization of scientific findings and supporting the decision making [19].

An Internet exploration through 8 databases (Scopus, Web of Sicence, Springer, Jstor, Science Direct, Wiley online Library, Emerald, Taylor & Francis online) and a search engine (Google Scholar), did not provide evidence of systematic or narrative reviews focused on the application of the BSC in Latin American HEIs. There are close studies, such as, for example, a narrative review on the practical application of the BSC in different industries [20], another on the application of the BSC considering environmental, social or ethical problems, called sustainability BSC [21], a systematic review of the strategies in non-profit organizations [22], and without being a review, an article from this year [23], in which the influence of the BSC on the research and innovation performance of six Latin American universities was studied. Of all the reviews found, the most related is a narrative review that focuses on the context of the BSC in IES [24], which identifies and contextualizes the perspectives.

Based on the above, this systematic review of the literature, with meta-analysis, aims to analyze how the BSC has been adapted as a tool for strategic management in Latin American HEIs, discovering what type of relationship exists between the variables of the tool and the characteristics of the organizations who have evidenced their application through publications.

This document is structured according to what Denyer and Tranfield proposed for a systematic review in the area of management [25], to which a section with the meta-analysis is added, as follows: in Chapter 2 describes the methodology used, then the results are presented and discussed, in section 4 the meta-analysis is evidenced, to end with the conclusions.

2 Methodology

The systematic review was carried out based on the methodology proposed by Denyer and Tranfield[10] [25], which consists of four steps.

[9] Although there is no single definition, it can be established that a systematic review is an academic research article that synthesizes studies through planned, explicit, transparent, and repeatable procedures to answer predefined questions.

[10] This methodology is applied since it focuses on the field of management.

2.1 Question formulation

The basic question is: In what way has the BSC been applied in strategic processes of different types of Latin American HEIs?

Reformulating the question according to the CIMO logic [25], acronym of Context, Intervention, Mechanism and Outcome, it results: Are the characteristics of an HEI (context) a determining factor (intervention) in the definition of the perspectives and objectives of the BSC (outcome)? How (mechanism) affect the design of the BSC (result)?

2.2 Location of studies

The exploration was carried out using the 9 search engines mentioned in the previous section, to which the academic platform Academia.edu was added, using keywords, Boolean operators, truncation, and special characters, to the extent that the search engine allowed it **Table 1**.

Table 1. Techniques used to search for studies.

Search identifier	*Search settings*
A	balanced scorecard higher education strategic management
B	cuadro de mando integral educación superior gestión estratégica
C	(TITLE ("balanced scorecard") AND ABS (higher AND education AND strateg* AND management) OR TITLE-ABS-KEY (strateg* AND management AND universit*))
D	"strategic management" argentina perspectives financial learning internal process customer indicators "balanced scorecard" "higher education institution"
E	strategic management argentina perspectives indicators "balanced scorecard" "higher education institution"
F	strategic management perspectives indicators argentina "higher education institution" "balanced scorecard"
G	strategic management perspectives indicators chile "higher education institution" "balanced scorecard"
H	gestión estratégica perspectiva indicador "institución de educación superior" "cuadro de mando integral"
I	gestión estratégica perspectiva indicador educación OR superior "cuadro de mando integral" -empresa -salud

An exploration was carried out with the keywords in English and Spanish, and then a more detailed search was carried out, testing different combinations, discarding the first since they were very inefficient (produced more than 500 results), using one at a time the name of different countries, until the use of the Spanish language without country restriction generated positive search results.

2.3 Study selection and evaluation

The following three selection criteria were used.

The first is that the BSC was applied in a Latin American HEI. Latin American countries are defined as: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba,

Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Dominican Republic, Uruguay and Venezuela [10].

It is understood "application of the BSC" according to the definition made by its creators [12], in which perspectives, objectives and indicators are identified. Therefore, if any of the first two is not present, the document is not considered.

Finally, the application must be about an organization that provides HE services, regardless of the type of degree or title that it delivers, its owner/administrator, or its teaching modality; but parts of it are not considered, that is, academic units, departments, centers, institutes, faculties, among others, nor are the institutions that train members of the armed forces.

The second criterion is that the BSC was used within the context of a strategic process. Applications that include strategic objectives are considered.

And the last criterion was that the HEI was identifiable in terms of the owner, destination of its benefits and type of institution. Are considered both public and private institutions, for-profit and non-profit institutions, and those that teach study programs levels 5 and / or 6 according to international standards [26].

2.4 Analysis and synthesis

A form was used for data extraction, with the following aspects:

- Publication: Search engine - Year - Research name - Author (s) - Type of publication (paper, thesis, conference proceeding, degree or professional seminar, monograph, working paper, or dissertation) – Country.
- Research design: Research objective - Name of the Institution - Type of organization according to its owner (public or private) - Type of HEI according to its mission (university, technical institute or professional institute) - Number of students – Institution's age - Participation of representatives of the organization in the study.
- Application of the BSC: - Map (yes / no) - Perspectives - Strategic objectives - Number of indicators.

2.5 Report and use of the results

Finally, the report is generated, in which the research is contextualized and justified, the results obtained are presented, the analysis is carried out and the research questions are answered.

To this is added a meta-analysis, in which the studies are statistically combined, which allows a more technical analysis with a greater scope.

3 Findings and discussion

Once the search was carried out through the procedure described, it yielded different results with the different search engines.

From the review of the documents applying the selection and evaluation criteria described above, positive results were obtained only through the Google Scholar search engine and the Academia.edu platform. The exploration revealed a total of 17 documents that met the established selection criteria, using H and I techniques (**Table 1**).

In publication aspect, the distribution of researches over time (**Fig. 2**) shows that it was not until 2000 that the first evidence of a study was found in which the BSC was applied to a strategic planning process in a Latin American HEI, with a slight increasing trend towards 2018.

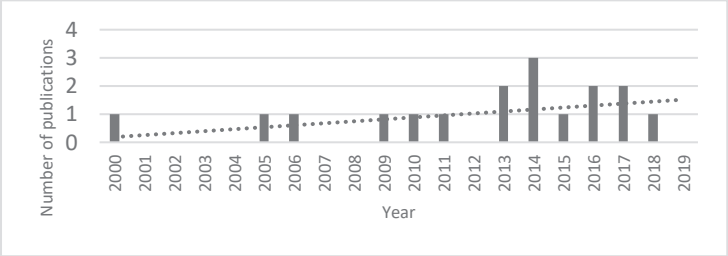

Fig. 2. Number of documents found (January 2000 - October 2019)

Regarding the country of origin of these documents, the majority came from Colombia, Ecuador and Venezuela, representing almost 80% of the publications found (**Fig. 3**).

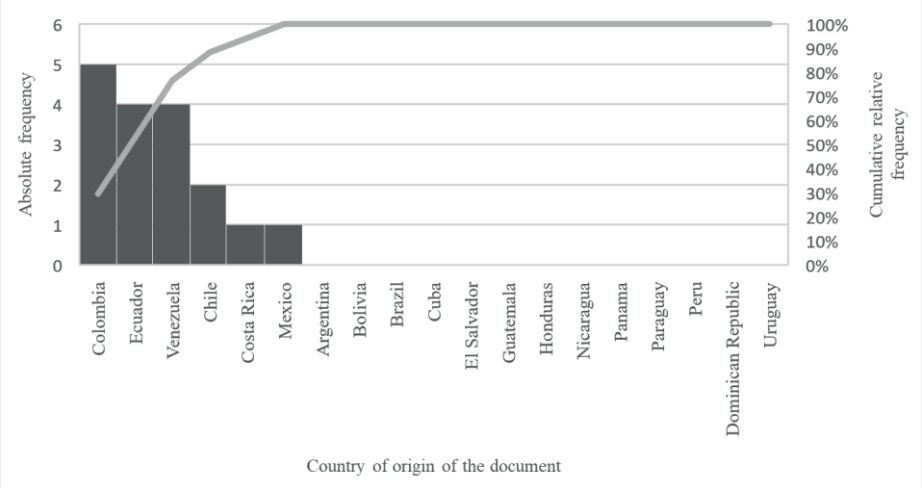

Fig. 3. Most frequent countries of origin of the 17 documents found.

The documents found are of the following classes: Degree Seminar, Paper, Thesis, Monograph, Professional Seminar, and Conference Publication. In **Fig. 4** it can be observed that most of the works (64%) correspond to degree seminars and papers.

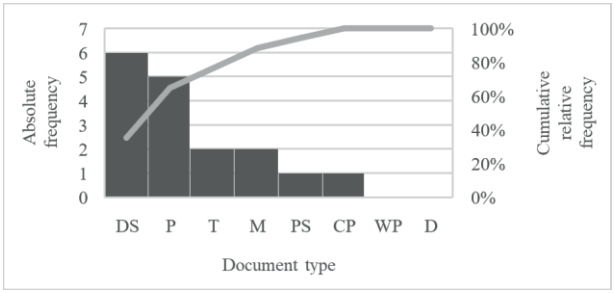

Fig. 4. Most frequent types of document (DS=degree seminar, P=paper, T=thesis, M=monograph, PS=professional seminar, CP=conference proceeding, WP=working paper, D=dissertation).

Categorizing according to the level of education of the organizations in which the research was carried out, by a large majority the researches were carried out in universities, with 70.6%, and the rest correspond to non-university HEIs. And according to the classification by type of property, 59% of the researches were carried out in public institutions and the remaining 41% in private organizations.

Within the aspects related to the research design, such as the number of students, the age of the institution and the participation of representatives of the organization in the study, they could not be considered because only partial information was found. Something similar with aspects of the application such as the strategy map or the indicators; the analysis could not be made considering that very few valid documents were found, and that 35% did not include the map, and 18% did not include indicators.

Regarding the perspectives used in each study, these are detailed in **Table 2**, and it can be inferred that in almost all the works (16 of 17) four perspectives are established, that is, the same number of dimensions as those originally proposed by Kaplan and Norton [12] [13]; there is only one study that proposes five. In addition, it is striking that only 1 of the 16 studies after 2001 considers the adaptation to non-profit organizations made by the authors of the BSC in that year [14].

Table 2. Documents found of the application of the BSC in strategic processes of Latin American HEIs.

Year	*Author(s)*	*Name of research*	*Perspectives*
2018	Barrera, Juan.	Propuesta de Diseño de una herramienta de gestión para fortalecer la administración y facilitar la toma de decisiones Universidad San Buenaventura Cali.	1) Financial 2) Customer 3) Internal processes 4) Learning and innovation
2017	Boglio, Alejandro.	Propuesta de un sistema de Control de Gestión para el Centro de Formación Técnica Juan Bohón - La Serena	1) Financial 2) Customer 3) Internal processes 4) Learning and knowledge
2017	Guevara, Olimar.	Cuadro de Mando Integral como herramienta estratégica para la efectividad de la gestión universitaria	1) Financial legal 2) Customers External/internal 3) Internal processes 4) Learning and growth
2016	Mendivil, Guillermo .	Diseño de un modelo de gestión con las herramientas del Cuadro de Mando Integral (CMI) o Balanced Scorecard para el Instituto Nacional de Formación Técnica Profesional de San Andrés, INFOTEP	1) Community 2) Customer 3) Internal processes 4) Learning and growth

2016	Panesso, Carlos; Jaramillo, Ana.	Modelo Balanced Scorecard para el Instituto de Educación Técnica Profesional INTEP de Roldanillo Valle del Cauca	1) Society 2) Customer 3) Internal processes 4) Learning and growth
2015	Gamarra, Mauricio; Poveda, Eidis.	Actualización del Balanced Scorecard de la Fundación Universitaria Tecnológico COMFENALCO	1) Customer 2) Processes and projects 3) Learning and growth 4) Financial
2014	Villacís, Allison.	Diseño del Prototipo para un Sistema Automatizado de Administración de Indicadores de Gestión de Calidad aplicado en una Institución de Educación Superior (IES)	1) Student training 2) Teacher development 3) Research 4) Relationship with society
2014	Samaniego, Víctor.	Medir la capacidad del desempeño administrativo y académico basado en el plan estratégico del Instituto Bolivariano.	1) Financial 2) Customer 3) Internal processes 4) Learning and growth
2014	Arias, David; Vélez, Yadira.	Plan estratégico y Balanced Scorecard para la PUCE SD, periodo 2014-2018	1) Financial + Customer 2) Internal processes 3) Learning and growth
2013	Armas, Gladys.	Cuadro de Mando Integral como herramienta para el seguimiento del Plan Estratégico de la Universidad José Antonio Páez	1) University management 2) Students and community 3) Internal processes 4) Infrastructure and technology 5) Human talent
2013	Alvarado, Luis; Aguilar, Alfredo; Cabral, Agustín; Alvarado, Tomás.	Diseño de un sistema de planificación estratégica basado en el Balanced Scorecard: El caso de la Antonio Narro	1) Finance 2) Customer 3) Internal processes 4) Training and growth
2011	Muñoz, Jorge.	Balanced scorecard-BSC o cuadro de mando integral-CMI para la Universidad Nacional de Loja	1) Students 2) Financial 3) Processes 4) Learning and growth
2010	Vega, Mayela.	El modelo de planificación estratégica en la Universidad Nacional 2004-2009 y una propuesta de un nuevo modelo basado en el uso del Cuadro de Mando Integral	1) Priority population 2) Financial management 3) Substantive rationality 4) Human talent
2009	Alana, Bolivar.	Planificación Estratégica Para La Universidad Adventista De Chile, 2005-2007	1) Institution 2) Customer 3) Internal processes 4) Learning and development
2006	Bastidas, Eunice; Moreno, Zahira.	El Cuadro de Mando Integral en la gestión de las organizaciones del sector público: El caso Universidad Centroccidental Lisandro Alvarado.	1) State 2) Society 3) Internal processes 4) Organizational learning and development
2005	Arias, Leonel; Castaño, Juan; Lanzas, Angela.	Balanced Scorecard en instituciones de educación superior	1) Society 2) Customer 3) Processes 4) Training and growth
2000	López, Yoleiza.	Hacia un Cuadro de Mando Integral para el Instituto Universitario Experimental de Tecnología "Andrés Eloy Blanco"	1) Financial 2) Customer 3) Internal processes 4) Training and growth

To know which are the perspectives in which there is greater consensus to use within the institutional strategic processes of Latin American HEIs, the frequencies for each perspective were calculated.

In a first approach, the perspectives were considered as they were defined in their original studies, without applying association criteria between them. The product of this raw analysis is shown in **Fig. 5**. The most used perspectives turned out to be the 4 defined by Kaplan and Norton [12] [13], and in the following order: 1st Internal processes, 2nd Costumer, 3rd Financial, 4th Learning and growth.

Then, an adjustment was made to the perspectives found, in order to associate them according to how they were defined by their authors [12] [13] and to the approach or explanation given for each of them by the authors of the respective studies, obtaining the result of **Table 3**. From these it can be inferred that all the perspectives used in the researches can be associated with some perspective of the original Kaplan and Norton BSC. This link is summarized in **Fig. 6** and **Fig. 7**.

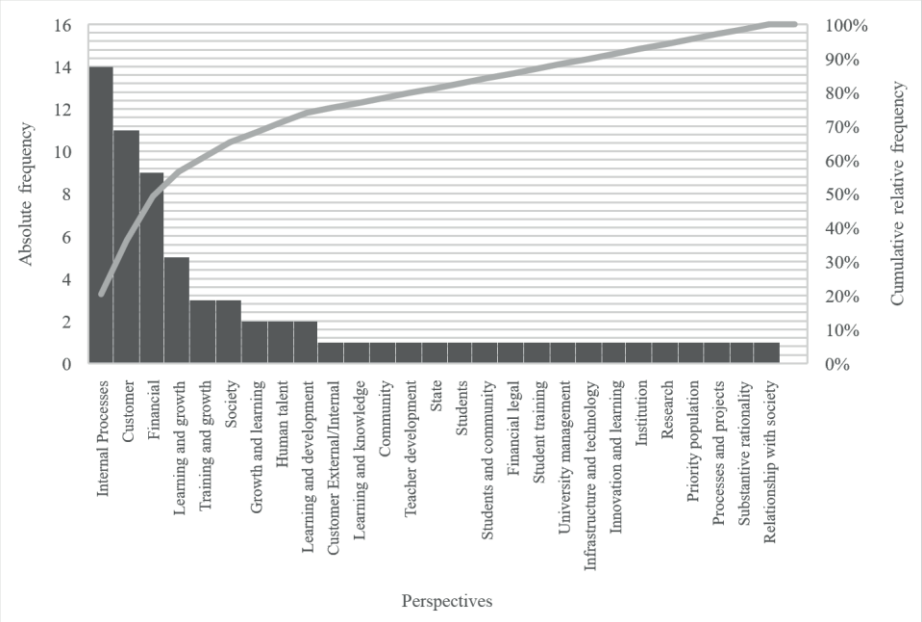

Fig. 5. Perspectives most found in documents on the application of the BSC in Latin American HEIs in the context of their strategic planning.

Table 3. Linking the perspectives established in the BSC applications found with the 4 original perspectives of Kaplan and Norton.

Kaplan and Norton perspectives	Associated perspectives of documents
Learning, development, and innovation.	Learning and knowledge Learning and growth Learning and development Growth and learning Training and growth Innovation and learning Teacher development Human talent Infrastructure and technology
Customer.	Customers Community Society Relationship with society State Students Students and community Institution Research Priority population
Financial.	Financial Financial management University management

Internal processes.	Internal processes Processes and projects Student training Substantive rationality

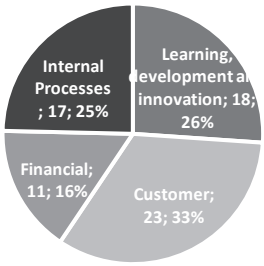

Fig. 6. Use of the original 4 perspectives of Kaplan and Norton in the documents found.

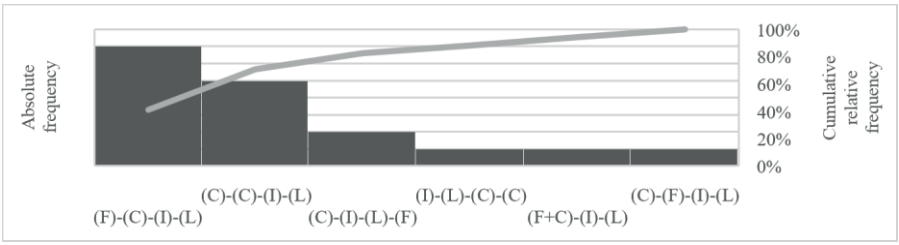

Fig. 7. Structure of perspectives most used, where: F = Financial, C = Customers, I = Internal processes, and L = Learning, development, and innovation.

It can be deduced, from these graphs, that the "Customers" dimension is the most considered of the four perspectives (33%) to generate strategic objectives, and at the same time the "Financial" perspective is the least considered (16%).

In addition, if the structure of perspectives is analyzed, that is, at what levels are located each of the strategic areas (**Fig. 7**), the most frequently used is the one originally suggested by Kaplan and Norton for the generation of the BSC in companies, this is: First level: Financial, Second level: Costumer, Third level: Internal processes, Forth level: Learning, development, and innovation.

The only case (mentioned above) that structures its perspectives according to the suggestion of Kaplan and Norton for non-profit organizations stands out within all the studies, that is: First level: Financial + Costumer, Second level: Internal processes, Third level: Learning, development, and innovation.

4 Meta-analysis

Given the need to relate nominal qualitative variables, contingency tables were developed to generate two analyzes based on the chi-square test.

4.1 Relationship between the Property of the HEI and the strategic level of the Financial perspective

The first goal was to find out if there is a relationship between two variables: the "property of the HEI" and the "level at which the Financial perspective is situated within the structure of the BSC".

For this, the following null hypothesis was raised:

H0 = The ownership of the HEI and the strategic level at which the financial perspective is situated are independent variables.

First the corresponding contingency table was designed **Table 4**, composed of the observed frequencies fij, for the financial perspective in public and private HEIs.

Table 4. Contingency table for the location of the financial perspective in public and private HEIs.

	Location of the Financial perspective			
Owner of the HEI	***Level 1***	***Level 2***	***Level 3***	***Level 4***
Public	3	2	0	0
Private	5	0	0	1

From this, the expected frequencies eij were obtained, to finally calculate the observed chi-square statistic using the expression (1):

$$\chi^2 = \sum_i \sum_j \frac{(f_{ij} - e_{ij})^2}{e_{ij}} \qquad (1)$$

The theoretical value of chi-square, 5,99, was obtained for a probability of 5%, and only 2 degrees of freedom of the original 3, since the third column was not considered, in which the expected frequencies were zero, product that the financial field in none of the applications was considered for level 3 of the BSC.

The observed result was, then, χ ^ 2 = 3,44, less than 5,99, so the null hypothesis is not rejected and, therefore, it can be stated that the variables "Property of the HEI" and the "Level at which the Financial perspective is situated within the structure of the BSC", are independent.

4.2 Relationship between the property of the HEI and the perspectives used

In a second analysis, the objective was to find out if there is a relationship between the "Property of the IES" and the "Perspectives used".

For this, the following null hypothesis was raised:

H0 = The ownership of the HEI and the perspectives used are independent variables.

Table 5 shows how the different original perspectives of Kaplan and Norton were used in private and public HEIs. From this, the corresponding contingency table was constructed (**Table 6**), composed of the observed frequencies fij for the different perspectives in public and private HEIs, which served as the basis to obtain the expected frequencies eij.

Table 5. Absolute frequencies of use of the perspectives in the different levels of the BSC according to the property of the HEI.

	Financial				*Costumers*				*Internal processes*				*Learning, development, and innovation*			
Owner of the HEI \ Level	***1***	***2***	***3***	***4***	***1***	***2***	***3***	***4***	***1***	***2***	***3***	***4***	***1***	***2***	***3***	***4***
Public	3	2	0	0	6	7	1	1	1	0	9	0	0	1	0	9
Private	5	0	0	1	3	5	0	0	0	2	5	0	0	0	2	5

Table 6. Contingency table for the use that is given to the different perspectives in public and private HEIs.

Owner of the HEI \ Perspective	***Financial***	***Customer***	***Internal processes***	***Learning, development, and innovation***
Public	5	15	10	10
Private	6	8	7	7

The chi-square statistic, calculated through (1), gave a value of 1,20.

Then, the theoretical value of chi-square 7.81 is obtained, for a probability of 5% and 3 degrees of freedom.

The result, then, is that χ ^ 2 = 1,20 is less than 7,81, so the null hypothesis is not rejected and, therefore, the variables "Property of the IES" and "Perspectives used", are independent.

5 Conclusion

There is a growing use of the BSC in support of the strategic processes of the institutions, which are key to the consolidation and sustainability of them, considering the demands posed by the new regulations in the HE systems (accountability, quality, strategic development plans, among others).

The association of the perspectives used with the original ones by Kaplan and Norton shows that the perspective that was most considered in the different strategic levels of the BSC was that of "Costumers" (in its broadest sense), evidencing the concern that HEIs have for their stakeholders[11].

HEIs tend strangely to reproduce the original structure of the Kaplan and Norton BSC model, originally aimed at companies, and not at educational services organizations, where the "Financial" perspective is established at the first strategic level. At the opposite hand, there were cases that did not consider the financial dimension, which, according to the meta-analysis, is not related to the ownership of the HEI; based on the application of the Chi-square test, there was no evidence of a relationship between ownership of Latin American HEIs (public or private) and the level at which it is situated,

[11] Internal stakeholders: students, academics, administrators, and managers. External stakeholders: employers, former students, parents and guardians, society in general, the government and its agencies, education providers, and non-governmental organizations [28].

or whether or not it represents the cornerstone of the strategy the "Financial" dimension; nor is there a specific structure of perspectives considered that reflects the differences between public and private institutions of HE.

Based on the above, it is striking that the adaptation to non-profit organizations, carried out by their authors, which recognizes the importance of mission in HEIs, has not had a great impact on the strategic planning processes of HEIs, since its appearance 19 years ago. This opens up a field of development for these processes and shows that more experience is needed in Latin America and, above all, knowledge of the results obtained from their use, in order to generate scientific conclusions about the impact that the BSC is having in this strategic and fundamental sector for the development of people and societies.

On the other hand, the systematic review and meta-analysis allowed to summarize part of the strategic planning of Latin American HEIs and, adapted to their context, they are projected as very useful and reliable tools to observe how management in higher education will continue to develop.

It is concluded, then, that the incipient use observed of the BSC in Latin America is independent of the type of HEI or the system in which it is immersed, becoming an instrument of transversal management, in a strategic process that is fundamental for an adequate management of these organizations in the current complex and challenging context.

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Visão Baseada em Recursos: O uso da tecnologia *Blockchain* na Gestão do Conhecimento

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Resumo. A Visão Baseada em Recursos é uma teoria que ao ser aplicada pode proporcionar vantagens competitivas para as empresas. Desta forma, o presente artigo busca analisar, por meio da lente da Visão Baseada em Recursos, dois recursos organizacionais: conhecimento e tecnologia. O conhecimento, por meio da Gestão do Conhecimento, que consiste nas atividades de criar, compartilhar e utilizar o conhecimento oferecido pelas pessoas inseridas e relacionadas à organização, e a tecnologia abordando o *Blockchain*, tecnologia por trás da criptomoeda Bitcoin. Assim, o objetivo deste artigo é identificar como a adoção da tecnologia *Blockchain* tem sido utilizada para aprimorar as capacidades dos recursos de Gestão do Conhecimento. O aspecto metodológico utilizado na pesquisa trata-se da *Fast Systematic Literature Review,* caracterizando a pesquisa como uma Revisão de Literatura. O estudo identificou como principal resultado que a tecnologia *Blockchain* tem sido aplicada na função de compartilhamento do conhecimento e tem atuado em questões como falta de confiança entre os membros das organizações, falta de transparência e segurança, permitindo uma melhor utilização desse conhecimento, gerando oportunidades de valor e promovendo vantagens competitivas para a empresa.

Palavras-chave: Visão Baseada em Recursos, *Blockchain*, Gestão do Conhecimento.

1 Introdução

No contexto em que as empresas se encontram atualmente existe uma dificuldade crescente de criar diferenciação perante seus concorrentes. A eficiência operacional já não é o suficiente, havendo um esgotamento dos modelos baseados apenas na eficiência, surgindo assim a necessidade de incorporação, por parte das empresas, de outras dimensões que complementam o quadro multidimensional do desempenho organizacional [1].

A concorrência global passou a ser "sem fronteiras", uma vez que os limites tradicionais como fronteiras nacionais têm diminuído de significância. Coordenar as atividades geograficamente dispersas para obter e manter vantagem competitiva é um dos desafios das empresas que competem globalmente. Nesta perspectiva que a economia baseada no conhecimento e o conhecimento como fator competitivo ganharam importância [2].

Além disso, para que as organizações consigam sobreviver em um ambiente tão competitivo, devem promover sua capacidade de aprender e incorporar novas práticas

e tecnologias em busca de melhorar seu desempenho e sucesso organizacional a longo prazo [3].

Neste contexto incorpora-se a teoria da Visão Baseada em Recursos. Esta teoria sugere que as empresas competem com base em seus recursos e capacidades. Estabelece que os recursos internos das organizações são responsáveis por proporcionar vantagem competitiva para as mesmas [4; 5; 6].

Assim, considerando o exposto, este artigo possui como objetivo analisar, por meio da lente da Visão Baseada em Recursos, dois recursos organizacionais: conhecimento e tecnologia. No que diz respeito ao conhecimento, este passa a ser estudado por meio da Gestão do Conhecimento, representada aqui pelas funções de identificação, aquisição, desenvolvimento, compartilhamento e distribuição, utilização e retenção do conhecimento [7].

A tecnologia estudada, por sua vez, trata-se do *Blockchain*, tecnologia por trás da criptomoeda Bitcoin, e que está tornando-se cada vez mais popular para simplificar processos de negócios e compartilhar dados, representando um sistema descentralizado, com transações transparentes e rastreáveis [8].

No que se refere à Gestão do Conhecimento, a sua execução dentro das empresas, considerando o atual cenário em que se encontram e a revolução da tecnologia, apresenta alguns desafios, dentre eles questões relacionadas ao armazenamento de conhecimento e problemas de compartilhamento de conhecimento e motivações, especialmente quanto à direitos autorais [9].

Neste sentido, a tecnologia *Blockchain* tem sido explorada como forma de solucionar alguns desses problemas, com destaque aos problemas de compartilhamento do conhecimento. Assim, com esta análise busca-se identificar como a adoção da tecnologia *Blockchain* tem sido utilizada para aprimorar as capacidades dos recursos de Gestão do Conhecimento.

2 Referencial Teórico

Nesta seção serão abordados os tópicos: (i) Visão Baseada em Recursos; (ii) Gestão do Conhecimento; e (iii) *Blockchain*, afim de compor o referencial teórico da pesquisa.

2.1 Visão Baseada em Recursos

A teoria da Visão Baseada em Recursos (*Resource Based View* – RBV) apresenta que os recursos internos da organização proporcionam vantagens competitivas para as mesmas [4; 5; 6]. Essa teoria proporciona uma visão estratégica sobre cenários nas organizações, permitindo melhor compreensão de seus recursos internos, observando em quais recursos a empresa deve basear seu crescimento e sua estratégia [4]

Quando se fala em RBV, para ter uma visão mais clara do assunto é necessária uma melhor compreensão para o termo "Recurso". Entende-se por recurso, determinada circunstância que pode ser considerada como um ponto forte ou um ponto fraco de uma organização, podendo ser, por exemplo: conhecimento interno de tecnologia, pessoal qualificado, máquinas, procedimentos eficientes, contatos comerciais, entre outros [4].

Os recursos são importantes pelas atividades e serviços que podem ser prestados através dele, pois, em geral, um único recurso, dependendo da maneira que ele é

utilizado e empregado, pode prestar um número grande de serviços, sendo assim uma vantagem a ser explorada [10].

Desta forma, a análise fundamental da RBV é determinada pelos recursos que podem ser controlados pela empresa [11]. Como os recursos não se vinculam diretamente a um uso especifico, é comum valer-se de uma classificação para defini-los. Assim, são classificados como recursos tangíveis, como recursos humanos, de infraestrutura física na forma de tecnologias de processo e de produto, recursos materiais, informacionais e financeiros, e intangíveis, que podem ser encontrados no âmbito da cultura organizacional; na forma de rotinas organizacionais; know-how entre outros. Porém, os recursos por si só não produzem valor. Assim, há necessidade de selecioná-los, combiná-los e mobilizá-los via serviços em atividades e processos [12].

Um aspecto importante a se considerar é que "os recursos constituem fonte de vantagem competitiva para as empresas na medida em que formam capacitações organizacionais e por estas são mobilizados nos processos organizacionais e de gestão" [1].

2.2 Gestão do Conhecimento

O conhecimento tem adquirido uma crescente importância na sociedade contemporânea [13], sendo visto como recurso básico para a nova sociedade que emerge da atual reorganização de valores, crenças, estruturas sociais, econômicas e dos sistemas políticos [14]. Na perspectiva da teoria da Visão Baseada em Recursos, o conhecimento é tido como um recurso fundamental para a sobrevivência, estabilidade e crescimento das organizações [15].

Esse novo papel que o conhecimento vem adquirindo exige uma mudança no pensamento quanto à inovação na organização das grandes empresas [13] e é nesta perspectiva que a gestão proativa do conhecimento adquire função central no que se refere à competitividade organizacional.

Para o desempenho da inovação, influenciado por aspetos relacionados com a rede de operações, cadeia de abastecimento e valor, bem como pelas tecnologias de informação e comunicação que coordenam o fluxo de criação de valor, a participação dos stakeholders das empresas e a gestão da informação e do conhecimento são considerados elementos fundamentais [16].

A Gestão do Conhecimento baseia-se na ideia de que o recurso mais valioso de uma organização é o conhecimento das pessoas, e reconhece que quase todos os trabalhos envolvem conhecimento em algum nível, o que significa que o trabalho depende mais do conhecimento das pessoas do que das suas habilidades manuais. Isso significa que criar, compartilhar e usar conhecimento estão entre as mais importantes atividades das pessoas em qualquer organização [17].

Ocorre que o controle, aplicação e desenvolvimento eficientes do conhecimento, afim de o gerir e utilizar com eficiência é determinado pelas capacidades da Gestão do Conhecimento [18]. Nesta perspectiva, pode-se entender capacidade como sendo a habilidade de implementar e integrar recursos para atingir objetivos corporativos, assim como os resultados obtidos através do acúmulo da interação de longo prazo entre diversos recursos [19].

A gestão do recurso conhecimento consiste das possibilidades de desenvolvimento, de transformação e de utilização de diferentes formas de conhecimento [1]. Nesta perspectiva podem ser elencadas seis funções da Gestão do Conhecimento [7]:

- Identificação do conhecimento: o conhecimento, tanto interno quanto externo, não é automaticamente visível, por isso as organizações precisam criar transparência de modo a saber onde encontrar o conhecimento de que precisam, ou seja, localizar o conhecimento, dentro e fora da empresa;
- Aquisição: as empresas podem comprar o conhecimento que não conseguem desenvolver, assim, parte substancial do conhecimento das empresas deriva de fontes externas, como por exemplo: clientes, fornecedores e concorrentes;
- Desenvolvimento: envolve todos os esforços administrativos direcionados de forma consciente para produção de novas capacidades, e seu foco está na geração de novas habilidades, novos produtos e processos mais eficientes, por exemplo;
- Compartilhamento e distribuição: são considerados como fatores vitais para transformar informações isoladas em algo que toda organização pode utilizar; a distribuição consiste em compartilhar e disseminar conhecimento que já existe na organização;
- Utilização: a organização deve assegurar a aplicação do conhecimento em seu benefício, e para isso deve tomar providências afim de garantir que as habilidades e ativos sejam totalmente utilizados;
- Retenção: consiste nos processos de selecionar, armazenar e atualizar regularmente o conhecimento, de forma a proteger a empresa contra a perda de conhecimento.

Considerando o exposto, tem-se que a gestão do recurso conhecimento não se limita a gerenciar o conhecimento em si, mas sim, possibilitar um ambiente no qual o conhecimento possa ser mobilizado e utilizado em benefício da organização [1].

2.3 *Blockchain*

Conhecida como sendo a tecnologia por trás da criptomoeda Bitcoin, a tecnologia *Blockchain*, também chamada de "razão distribuída", tem aplicações muito além das criptomoedas ou do mercado financeiro [20]. Em um sentido restrito, *Blockchain* pode ser entendido como sendo uma forma de livro razão que combina blocos de dados e informações em uma ordem cronológica e registra os blocos de forma criptografada como uma razão distribuída que não pode ser adulterada ou falsificada [21; 22].

Em sentido amplo, pode ser definida como uma metatecnologia, tendo em vista que usa, dentre outros, estruturas de dados do tipo bloco para validar e armazenar dados, algoritmos de consenso para gerar e atualizar os dados e criptografia para garantir a transmissão desses dados e para acessar a segurança [22]. Ou seja, não é apenas uma técnica, mas sim um novo modelo de aplicativo de combina tecnologias da computação como armazenamento distribuído de dados, transações ponto a ponto descentralizadas e independentes, mecanismos de consenso, algoritmos de criptografia e modelo econômico [22; 23].

Para entender de forma mais aprofundada sobre o funcionamento do *Blockchain*, pode-se analisar aspectos entendidos como principais características que sustentam o funcionamento da tecnologia, sendo: descentralização, *detrusting*, transparência, rastreabilidade e irreversibilidade de registros:

a) Descentralização: a comunicação ocorre diretamente entre os pares, sendo as informações automaticamente compartilhadas e distribuídas entre os nós, sem a necessidade de um nó central, ou seja, cada nó armazena e envia informações para todos os outros nós [22; 24];

b) *Detrusting*: como é baseada em princípios de protocolos de rede ponto a ponto e métodos puramente matemáticos, a tecnologia cria relacionamentos de confiança entre os nós da rede e as estruturas de sistema distribuídas [22; 25];

c) Transparência com pseudonimato: cada transação e seu valor associado são visíveis para qualquer pessoa com acesso ao sistema. Porém, a quantidade de informações transparentes para um observador, no entanto, pode ser diferente e nem todo participante deve, obrigatoriamente, ter o mesmo acesso a todas as informações. Ainda, os usuários podem optar por permanecer anônimos ou fornecer prova de sua identidade para os outros. As transações ocorrem entre endereços *Blockchain* [22; 24; 26];

d) Rastreabilidade: cada bloco de informações da BLC possui as informações de data e hora, que servem para identificar, registrar e validar cada transação, o que garante a sua originalidade, melhora a transparência e reduz o custo da rastreabilidade das transações [22; 27];

e) Irreversibilidade de registros: para uma transação ser validada e adicionada a um bloco, ela precisa ser revisada pela maioria dos nós do sistema. E uma vez que uma transação é inserida no banco de dados e as contas são atualizadas, os registros não podem ser alterados, porque estão vinculados a todos os registros de transação que vieram antes deles (daí o termo "cadeia") [22; 24].

A partir da definição do que é a tecnologia *Blockchain*, pode-se avançar no que se refere à sua utilização. Para tal, utiliza-se como referência o framework de driver de valor do *Blockchain* – Tabela 1 proposto por [20].

Tabela 1 - Framework de driver de valor do *Blockchain*

Qual valor é procurado?		É um opção viável adotar a tecnologia?	Por que um *Blockchain* é preferível a um ledger centralizado? Que combinação de tecnologias se alinha com o valor perseguido?
Oportunidades de valor	**Drivers de valor**	**Viabilidade**	**Tecnologias apropriadas**
Transparência	Custo de transação	Escopo	Centralizado
Imutabilidade	Serviços adicionados	Recursos para adotar e manter	Distribuído
Privacidade	Limites de organização	Compreensão de risco	
Durabilidade e confiabilidade	Tomada de decisão autônoma	Regulamento	
Tolerância ao erro		Obrigações legais	

Democratização		Desempenho	
Segurança		Interoperabilidade	
Controle de risco			
Token			

Fonte: Adaptado de [20]

Esse framework fornece insights sobre as oportunidades de valor e em que contexto e ofertas de produtos ou serviços pode-se aplicar a tecnologia. Cada etapa da estrutura fornece perguntas e recomendações acionários à adoção e uso da tecnologia [20].

3 Metodologia

Nesta seção será apresentado o instrumento de intervenção utilizado para a seleção dos artigos do portfólio bibliográfico.

3.1 *Fast Systematic Literature Review*

A Revisão Sistemática da Literatura (*Systematic Literature Review* – SLR) é composta por um conjunto de tarefas que demandam tempo, como a definição dos termos de pesquisa, análises de conteúdo e relatórios escritos [28]. Assim, para a condução desta pesquisa, foi utilizado o método *Fast Systematic Literature Review* (FASTSLR), que suporta o diagnóstico, a validação e avaliação do conteúdo da pesquisa e busca minimizar erros, tanto em relação à qualidade do trabalho quanto ao planejamento e desenho da pesquisa, assim como possibilita reduzir o tempo de execução da revisão [28].

É composto por três etapas que de maneira resumida consistem em: Etapa 1 - composta por atividades de pesquisa e busca dos artigos; Etapa 2 – consiste em um processo de refinamento dos artigos encontrados na etapa anterior, utilizando um gerenciador de referência, cálculo de amostra e leitura dos artigos, parcial e integralmente; e Etapa 3 - caracteriza-se pelo uso do software MC3R para obtenção de relatórios e matrizes bibliométrica [28]. Assim, seguindo as orientações propostas para o método, são apresentadas as etapas realizadas nesta pesquisa.

Para esta pesquisa foi selecionada apenas a base de dados *Scopus*, por ser "o maior banco de dados de resumos e citações da literatura com revisão por pares: revistas científicas, livros, processos de congressos e publicações do setor" [Elsevier, 2020]. Os termos de busca selecionados, considerando a proposta da pesquisa, foram: *"knowledge management"*, *Blockchain* e *"distributed ledger"*. Os operadores utilizados foram AND e OR, conforme Tabela 2. Ainda, em relação ao tipo de documento foram selecionados apenas *"article"* e *"conference paper"*, e em relação ao ano de publicação foram selecionados trabalhos publicados entre 2017 e 2019, a fim de obter resultados e pesquisas recentes sobre a temática. Considerando estes critérios, o primeiro conjunto de dados é composto por 36 publicações.

Considerando a baixa quantidade de artigos encontrados para a pesquisa, a técnica de cálculo de amostra não foi utilizada. Neste sentido, passou-se direto à importação do conjunto para o gerenciador de referências. Assim, o primeiro conjunto de dados foi

importado para o gerenciador de referências "Mendeley" para a realização da análise das palavras-chave, resumo e título quanto à aderência ao tema. Desta análise retornou um conjunto de dados composto por dez publicações. A tabela 2 apresenta um resumo da FASTSLR realizada:

Tabela 2 - Resumo da FASTSLR realizada

Critérios de busca	
Base de dados	Scopus
Tipo de documento	Article / Conference paper
Ano de publicação	2017 / 2018 / 2019
Termos de busca	"knowledge management" / *Blockchain* / "distributed ledger"
Operadores	AND / OR
Pesquisa na base de dados	
"knowledge management" AND *Blockchain* OR "distributed ledger"	
Resultados	
Conjunto bruto de dados	36 publicações
Conjunto final de dados	10 publicações

Fonte: Elaborado pelos autores, 2019.

Importante destacar que das dez publicações que compõem o portfólio de pesquisa, apenas oito foram encontradas na íntegra. Assim, duas das publicações não puderam ser analisadas. Por fim, destaca-se que a terceira etapa do método também não foi realizada, tendo em vista que resultaria informações que não corresponderiam ao objetivo de pesquisa.

4 *Blockchain* e Gestão do Conhecimento

A Gestão do Conhecimento, reconhecida muitas vezes pelas funções de identificação, aquisição, desenvolvimento, compartilhamento e distribuição, utilização e retenção do conhecimento [7], apresenta alguns desafios para a sua execução. Questões de armazenamento de conhecimento que, em função do aumento do conhecimento gerado nas empresas, as forçam a empregar novas estratégias de armazenamento, e problemas de compartilhamento de conhecimento e motivações, especialmente quanto a direitos autorais, uma vez que as empresas precisam garantir que seus especialistas, sobre seus direitos, compartilhem seus conhecimentos, são alguns dos exemplos de desafios enfrentados pela gestão do conhecimento [9].

Outro desafio enfrentado diz respeito à confiança. As atividades de gestão do conhecimento requerem uma cultura de confiança entre os membros de uma organização, sendo a falta de confiança uma das principais razões para o não compartilhamento do conhecimento entre os membros de uma organização [29].

A tecnologia *Blockchain* tem sido utilizada como um meio de solucionar alguns dos desafios enfrentados pela Gestão do Conhecimento. A função da Gestão do Conhecimento que tem ganhado mais atenção dos pesquisadores em relação a aplicação do *Blockchain* é o compartilhamento do conhecimento. Esta função do conhecimento, em relação à obtenção de vantagem competitiva por meio de recursos, proporciona aos

indivíduos, equipes e empresas a oportunidade de melhorar seu desempenho no trabalho, bem como criar novas ideias e inovações [30].

No que se refere a esta função, a tecnologia *Blockchain*, vista como um livro razão descentralizado e confiável, garante imutabilidade, confiabilidade e responsabilidade. Agregando a esta os contratos inteligentes, também é possível gerar melhorias na transparência e segurança nos procedimentos de compartilhamento de conhecimento [31].

Outro trabalho desenvolvido envolvendo estes dois recursos é o de [32], onde os autores buscam propor e desenvolver uma plataforma segura e confiável de compartilhamento de conhecimento em indústrias de moldes, observando que essas indústrias precisam, no que se refere ao compartilhamento, de colaboração com outras indústrias e de uma plataforma confiável. A plataforma proposta utiliza duas tecnologias avançadas: nuvem privada e *Blockchain*. Esta segunda tecnologia é implementada como uma rede distribuída para compartilhar conhecimento e registrar transações, permitindo a redução do risco do compartilhamento na plataforma.

Foi essencialmente projetada com vistas à resistência na modificação de dados, pois busca fornecer um método seguro para garantir a imutabilidade dos dados. Além disso, a verificação de associação possível a partir do *Blockchain* também possibilita garantir a validade das informações, uma vez que destaca a qualidade e responsabilidade de cada membro envolvido no compartilhamento do conhecimento [32].

Outro trabalho que busca aplicar o *Blockchain* à função do compartilhamento do conhecimento foi desenvolvido por [31], por meio do qual os autores propõem um sistema denominado *Reputation Based Knowledge Sharing* (RBKS), ou Compartilhamento de Conhecimento Baseado em Reputação, desenvolvido tendo como base o *Blockchain*. O objetivo desse sistema é explorar a proteção dos direitos autorais do dono do conhecimento por meio de esquemas de controle de acesso.

O modelo de gestão do conhecimento denominado *Block Chained Knowledge Management Model* (BCKMM), apresenta cada usuário como um nó da rede *Blockchain* e todo conhecimento acrescentado a rede é considerado uma transação. Quando uma pessoa necessitar de algum conhecimento e buscá-lo junto a rede, estarão disponíveis também todas as transações anteriores relacionadas àquele conhecimento [9].

Ainda, no modelo proposto todos os funcionários de uma empresa que façam parte da rede poderão registrar e compartilhar seus conhecimentos com todos os demais funcionários, e o seu conhecimento será retido e manterá as questões de propriedade e rastreamento, em um ambiente seguro [9].

[33] também abordam a aplicação do Blockchain direcionado ao conhecimento, mais especificamente como ferramenta de processamento rápido e seguro de ativos intelectuais e trocas de ideias, pois é capaz de fornecer um alto nível de confiança para a transferência do conhecimento.

Segundo os autores, a comunicação é o processo central na economia de conhecimento e experiência. Neste sentido, expõem que as principais preocupações de segurança da informação se concentram em tecnologias de transferência de conhecimento, cadeias ou redes de criação de valor, e de comunicação, dentro e fora das instituições. A tecnologia pode fornecer um ambiente mais seguro e confiável para as neuro-comunicações, a transferência direta de conhecimentos, experiências e sentimentos, incluindo a percepção de uma realidade [33].

[34] por sua vez, apresentam uma plataforma desenvolvida para construir um ambiente multi-nuvem a fim de compartilhar e reutilizar dados e conhecimento. Além disso, projetam um mecanismo de compartilhamento conhecimento, que usa um blockchain para registro e uso de serviços de processamento de dados, para que as entidades possam validar a integridade do histórico do processo.

Para além do compartilhamento do conhecimento, [35] expõem que o conhecimento vem sendo mal interpretado e manipulado para atender a diversos fins, sendo que informações de fontes confiáveis são muitas vezes abafadas por "fatos" de proveniência duvidosa. Explicam que não é suficiente simplesmente estabelecer a proveniência do conhecimento se esses meta-dados puderem ser alterados posteriormente. Com isso, estudam uma possível solução usando blockchain para gerenciar a proveniência do conhecimento.

O modelo implica que, como as informações na blockchain não podem ser alteradas, a proveniência do conhecimento é inerentemente mais confiável. Assim, a plataforma estudada busca ser segura para que as instituições de conhecimento publiquem fatos e forneçam a proveniência do conhecimento, assim como busca possibilitar a responsabilização dos atores sociais, como governos ou empresas. O modelo aproveita as propriedades descentralizadas do blockchain para atingir esses objetivos [35].

[36] também vão além da função de compartilhamento do conhecimento ao buscarem estudar o problema da erosão do conhecimento como resultado do crescimento explosivo de dados e informações, oferecendo um conceito baseado no sistema de objetos de aprendizagem protegido com o uso de blockchain permitido para minimizar os resultados negativos dos fenômenos de erosão do conhecimento.

A tecnologia blockchain é estudada como meio de manutenção de registros, garantindo a preservação de registros e prevenção de alterações não autorizadas neles. Segundo os autores, o núcleo do conhecimento científico geral deve ser protegido da distorção espontânea e requer uma transferência completa e garantida sem distorção. A proteção efetiva do núcleo de conhecimento deve ser combinada com um mecanismo regulatório que proporcione a possibilidade de sua edição apenas no caso de um consenso constante de especialistas [36].

A tabela 3 busca sintetizar as informações apresentadas e obtidas por meio dos artigos da revisão:

Tabela 3 – Aspectos da Gestão do Conhecimento e melhorias buscadas com o blockchain

Aspectos da Gestão do Conhecimento	**Melhorias com o blockchain**	**Autor**
Compartilhamento: oportunidade de melhorar seu desempenho no trabalho, bem como criar novas ideias e inovações.	Imutabilidade, confiabilidade e responsabilidade. Com contratos inteligentes: transparência e segurança.	[30]
Compartilhamento do conhecimento e direitos autorais.	Explorar a proteção dos direitos autorais do dono do conhecimento por meio de esquemas de controle de acesso.	[31]
Indústrias que precisam de colaboração com outras	Resistência na modificação de dados (imutabilidade dos dados), e validade	[32]

indústrias e de uma plataforma confiável para compartilhar o conhecimento.	das informações, pois destaca a qualidade e responsabilidade de cada membro.	
Explorar a proteção dos direitos autorais do dono do conhecimento por meio de esquemas de controle de acesso.	Registro das transações anteriores relacionadas a um conhecimento, e retenção do conhecimento com manutenção das questões de propriedade e rastreamento, em um ambiente seguro.	[9]
Transferência de conhecimento, cadeias ou redes de criação de valor, e de comunicação, dentro e fora das instituições	Ambiente mais seguro e confiável para as neuro-comunicações, a transferência direta de conhecimentos, experiências e sentimentos, incluindo a percepção de uma realidade	[33]
Compartilhar e reutilizar dados e conhecimento.	Registro e uso de serviços de processamento de dados, para que as entidades possam validar a integridade do histórico do processo.	[34]
Estabelecimento da proveniência dos dados.	Por meio da descentralização e imutabilidade dos dados, fornecer segurança para que as instituições de conhecimento publiquem fatos e forneçam a proveniência do conhecimento, assim como busca possibilitar a responsabilização dos atores sociais.	[35]
Erosão do conhecimento como resultado do crescimento explosivo de dados e informações.	Manutenção de registros, garantindo a preservação de registros e prevenção de alterações não autorizadas neles.	[36]

Fonte: Elaborado pelos autores, 2019.

Assim, considerando o exposto, pode-se resgatar o *framework* de driver de valor proposto por [20 ANGELIS, J.; SILVA, E. R], no qual os autores apresentam as oportunidades de valor geradas pelo *Blockchain*. Das oportunidades de valor apresentadas, é possível identificar nas aplicações de *Blockchain* no compartilhamento do conhecimento, de forma expressa, a imutabilidade do conhecimento, a sua durabilidade e confiabilidade, transparência, segurança e controle de risco. Esses valores gerados com o uso do *Blockchain* permitem uma melhor utilização do conhecimento disponível na organização.

Pode-se identificar, neste sentido, a possibilidade de aumento da capacidade da Gestão do Conhecimento com a aplicação do recurso tecnológico *Blockchain*, isso porque este recurso permite uma maior implementação e integração do recurso conhecimento dentro da organização por meio do aprimoramento da função compartilhamento. Assim como também permite, principalmente por meio da característica de imutabilidade que fornece aos dados, obter resultados por meio do acúmulo da interação de longo prazo do recurso conhecimento.

5 Gestão Estratégica de Operações utilizando a Visão Baseada em Recursos

"A melhoria contínua, o aprendizado organizacional e o desenvolvimento de competências estão sendo abordados pela estratégia de operações à medida que as organizações evoluem" [37] Neste artigo, a Gestão Estratégica de Operações foi abordada através da teoria da Visão Baseada em Recursos, ou *Resource Based View (RBV),* que apresenta que os recursos internos da organização proporcionam vantagens competitivas para as mesmas na medida em que formam capacitações organizacionais e por estas são mobilizados nos processos organizacionais e de gestão [1; 4; 5; 6].

Assim, esta seção visa ilustrar um *framework* teórico conceitual a respeito da relação teórica entre a Gestão Estratégica de Operações, por meio da teoria da Visão Baseada em Recursos, lidando com os recursos: conhecimento, por meio da Gestão do Conhecimento, e tecnologia, analisando-se a tecnologia *Blockchain.* A RBV estudada neste artigo busca interligar os recursos abordados, como exibido a Figura 1.

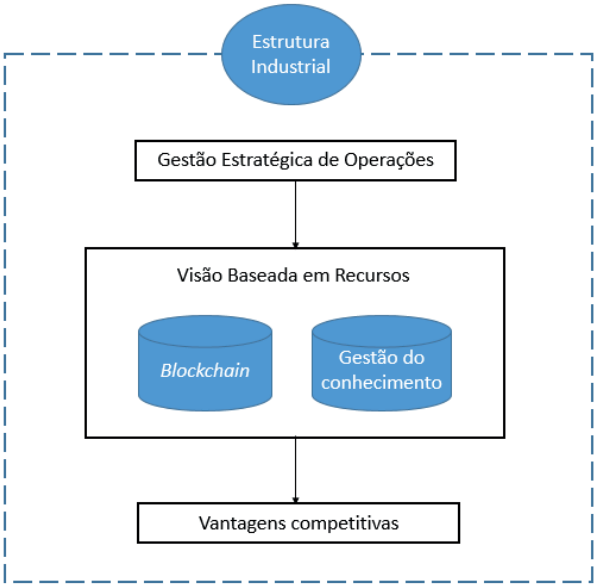

Fig. 1. Framework teórico conceitual
Fonte: Elaborado pelos autores, 2019.

Conforme ilustra a Figura 1, a Gestão Estratégica de Operações está inserida na Estrutura Industrial. Fundamentado nisso, relaciona-se a Visão Baseada em Recursos, que atua como um elo para associar a Tecnologia *Blockchain* e a Gestão do Conhecimento, buscando identificar como a combinação desses recursos podem desenvolver capacidades e reforçar seus papéis como fontes de vantagens competitivas para as organizações.

Desta forma o *framework* teórico conceitual desenvolvido, pode ser aplicado em segmentos industriais que utilizam a Visão Baseada em Recursos como uma estratégia para obter vantagem competitiva dentro da organização. A partir disso são designados os melhores recursos na organização, através dos quais a empresa poderá desenvolver suas estratégias e planejamentos. Sendo assim, determinando como recursos a tecnologia *Blockchain* e a Gestão do Conhecimento torna-se possível visualizar estratégias que podem ser empregadas na empresa, desenvolvendo uma melhoria contínua e uma boa gestão de operações.

6 Considerações Finais

O presente estudo, portanto, teve por objetivo analisar, por meio da lente da Visão Baseada em Recursos, dois recursos organizacionais: conhecimento e tecnologia. Com esta análise busca-se identificar como as capacidades dos recursos de Gestão do Conhecimento podem ser aprimorados com a adoção da tecnologia *Blockchain*. Para tal, buscou-se por meio do método *Fast Systematic Literature Review (FSLR)* artigos que abordassem ambos os recursos estudados para que fosse possível identificar de que forma estes dois recursos vem sendo relacionados.

Com a aplicação do método de revisão sistemática da literatura, FSLR, resultou-se em um portfólio composto por 10 (dez) artigos que abordavam ambos os assuntos estudados: Gestão do Conhecimento e *Blockchain*. Com esse conjunto de artigos foi possível compreender o assunto abordado e identificar de que forma a tecnologia *Blockchain* tem sido aplicada à Gestão do Conhecimento. Neste sentido, considerando a Gestão do Conhecimento a partir das funções de identificar, adquirir, desenvolver, compartilhar e distribuir, utilizar e reter o conhecimento, a tecnologia tem sido aplicada com maior foco à função de compartilhamento.

Por meio dos artigos, identificou-se que a tecnologia *Blockchain* tem possibilitado a resolução de alguns desafios que as empresas têm enfrentado na realização da Gestão do Conhecimento. Questões como falta de confiança entre os membros das organizações, falta de transparência e segurança são algumas das oportunidades de valor geradas pela tecnologia para a Gestão do Conhecimento, resultando em um melhor e maior compartilhamento de conhecimento dentro das organizações, sendo que um melhor compartilhamento de conhecimento fornece a oportunidade de melhorar o desempenho dos funcionários no trabalho, bem como criar novas ideias e inovações.

Em relação às limitações da pesquisa, devido ao fato de a tecnologia *Blockchain* estar ainda em estágios iniciais de desenvolvimento e aplicação, poucos casos foram encontrados na literatura, em especial casos que relacionassem a tecnologia ao tema Gestão do Conhecimento. Esta limitação, no entanto, pode ser vista como uma oportunidade de pesquisa.

Assim, este artigo expõe a necessidade de explorar novas aplicações da tecnologia *Blockchain* à Gestão do Conhecimento, principalmente sobre a lente da Visão Baseada em Recursos, destacando as implicações da combinação destes recursos para o desenvolvimento e potencial competitivo das organizações. Desta forma a presente pesquisa cumpre com o objetivo proposto, realizando uma revisão sistemática da literatura e acrescentando conhecimento ao tema proposto.

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Key Factors for the Implementation of New Technologies in Manufacturing Systems – Insights from Case Studies

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Abstract. Implications of Industry 4.0 and the key factors for an effective implementation is still unclear. This paper supports the understanding of what are the main success factors for implementing a new technology and what are the implications of these adoptions for the operations management. For this, cases studies were conducted regarding the implementation of new technologies in companies of the metal-mechanic and automotive sectors of the South and Southeast regions of Brazil, aiming to determine what are the key factors for a successful implementation under the analysis from a strategic and practice perspective. The results from the present research illuminates that even the financial and technology resources being relevant factors for a successful implementation, the main factors for an effective implementation are not related to the resources available but the way that they are being managed and integrated.

Keywords: management of operations, strategic dimensions, dimensions of practice.

1 Introduction

The term "Industry 4.0" became publicly known in 2011 through a German government initiative called "Industrie 4.0" and are being used to denote the fourth industrial revolution [1–3]. This revolution aims at a fusion of the physical and virtual word into cyber-physical systems (CPS) and was preceded by three other industrial revolutions that have driven dramatic increases in industrial productivity, being these related to the steam engine, mass production systems and automation technologies [4–9].

In the past few years, this topic became one of the most discussed topics in manufacturing conferences, forums and exhibitors and attracted interest of governments and industries worldwide regarding the benefits that this revolution could provide [10]. However, even with the increasing research attention on this topic, the implications of these technologies to the production systems is still unclear, being the academic papers

focusing excessively on the technologies, such as the Internet of Things (IoT) and technologies associated with large volumes of data (Big Data Analytics), without approaching their impact on management systems and the key factors for an effective implementation [10].

Based on this scenario, the present paper aims to support the understanding of what are the main success factors for implementing a new technology and what are the implications of these adoptions for the operations management. For this, nine cases studies were conducted regarding the implementation of new technologies in companies of the metal-mechanic and automotive sectors of the South and Southeast regions of Brazil, aiming to determine what are the key factors for a successful implementation under the analysis from a strategic [11] and practice perspective [12]. The case studies were developed using the case study protocol proposed by Brunheroto et al. [13], which emphasizes the strategic perspective of the change, using the strategic dimensions proposed by Pettigrew [11] as basis for its construction. For the analysis under a practice perspective, the protocol was reviewed using the dimensions of practice proposed by Nicolini [12] through a comparison between both approaches using a Quality Function Deployment (QFD) matrix, aiming to determine the most relevant aspects of the protocol under a more practical-based approach.

Therefore, the present paper is organized in five sections, besides this introduction. In the following section, concepts regarding the strategic dimensions proposed by Pettigrew [11] and the dimensions of practice proposed by Nicolini [12] are presented. Next, the case study protocol is presented. After that, the case studies conducted related to the implementation of new technologies are shown. Then, an analysis of the used case study protocol according to the Nicolini's [12] dimensions of practice is made. Finally, in the last section, conclusions obtained with the present research are drawn.

2 Theoretical background

2.1 Strategic dimensions

Strategic change can be defined as a radical alteration or substantial overhaul of previous organizational strategies, structures, and activities [14]. The starting point for the analysis of strategic change is the notion that formulating the *content* of any new strategy inevitably entails managing its *context* and *process* [11]. Based on that scenario, the present paper aims at the analysis of several case studies through a protocol based on the Pettigrew's strategic dimensions of *context*, *process* and *content*, which has been used as basis for several studies related to enterprise engineering [11, 13, 15–17].

First, in relation to the *context*, it can be defined as the circumstances under which process and content occur [18]. In other words, it is related to the *why* of the change and refers to the environmental forces and internal aspects that constrain and enable strategic changes at the firm level. This dimension can be subdivided into two main contexts: outer context, related to the aspects in which the firm operates (macro environment, sector, etc.), and inner context, related to the aspects of the firm itself (corporate culture, strategies, etc.) [11, 13, 19].

The *process* dimension is related to the *how* of change and is related to the actions, reactions, and interactions from the various stakeholders as they seek to move the firm from its present to its future state [11, 19]. This dimension can be subdivided in two main aspects: project, related to the methodologies and consequences of the process, and resources, which englobes the resources necessary for the process (financial, human, technological, etc.) [13].

Finally, the *content* dimension refers to what has changed in the organization or the product obtained by the implementation of the strategies [18]. This dimension is related to the *what* of the change and can be subdivided in the improvements regarding the performance objectives (dependability, cost, flexibility, etc.) and other improvements (sustainability, opportunities, etc.) [11, 13, 19, 20].

2.2 Dimensions of practice

Besides the strategic domain, practice-based approaches are also being used to study many complex settings, such as healthcare, biomedical engineering, government, and construction projects [21–24]. Based on that scenario, the present paper also intends to support the understanding of the similarities between both approaches. For this, the five dimensions of practice proposed by Nicolini [12] were also taken as basis, which are considered as a toolkit approach that allows a rich investigation of social reality [12, 25].

Regarding these dimensions of practice, the first one is related to the *work and efforts* and it is related to the work and efforts made to achieve its objective and helps the overcome the illusion that "rational" decision, plans or organization leads automatically to the effective project implementation. In other words, this dimension supports the enlightenment of the difficulties involved in a diversity of project activities from building a project concept to making consensus and cultivating relations between participants [25].

The second dimension is related to the *materially* and aims at the understanding of why some difficulties and unforeseen events are so frequently present in the projects. In other words, it helps to identify why projects are surprised by unforeseen events, why planning and sharing spaces on project sites is so difficult, why so many failures occur when projects start operation, among others [25, 26].

The *agency and creativity* dimension is related to reasons for the necessity of capabilities for the project development, planning, etc. [27]. In other words, it helps to understand why projects need competent, creative and active clients or sponsors to steer them in the right direction, why inertia takes hold of project organization during implementation, and so on [25].

The fourth dimension, *knowledge*, is related to the distribution of expertise and support the understand of how the knowledge is created, maintained, and used by the project participants. In other words, it helps to identify how the knowledge fails to transfer and mobilize from past projects or, conversely, how the project participants fail by over-relying on past knowledge [25, 28].

Finally, the dimension of *interests and power* illuminate shifts of authority and dependence patterns in temporary organizations, the conflicts, tensions, and aberrant

response to unexpected events that affect so many projects. In other words, it supports the understanding of the difficulties regarding organizational aspects, such as culture, leadership, internal conflicts and disputes [25, 29].

3 Research Design

For the present research, 9 case studies, including the pilot case, were conducted with companies from the metal-mechanic and automotive sectors of the South and Southeast regions of Brazil in relation to the implementation of new technologies. For the data collection, the protocol proposed by Brunheroto et al. [13] was used, which was based on the methodology proposed by Yin [30] for case studies and the strategic dimensions proposed by Pettigrew [11].

Regarding the case study conduction, it consisted in three main phases: data collection, data structuring and data analysis, similar to the methodology proposed by Cestari et al. [31]. In relation to these phases, an overview can be seen in Figure 1.

The first phase, data collection, happened in two main parts: the main collection and the additional collections. Regarding the main collection, it consisted of semi structured interviews with the responsible for the projects, aiming to collect general information regarding the case. In relation to these interviews, they were initially person to person, mainly through visit to the companies, and later by video conferences, due to pandemic scenario, being these interviews recorded with the interviewee permission for future analysis. The additional collections were made through questionnaires, documents, and structured interviews, and aimed at the collection of missing information that could not be collected in the semi structured interviews.

The second phase, data structuring, also happened in two main parts: transcription and organization. Regarding the transcription, it was made using a speech recognition program to automatically transcript the interviews, being later reviewed by the researchers aiming to identify any mistakes. After the transcription, the data obtained were organized according to the information requirements of the protocol, aiming to identify the need of any additional collection.

Finally, after the data collection and structuring, the third phase took part, where all the information was synthesized in keywords or key phrases for a better understanding of the case, being this information later analyzed for the conclusions making.

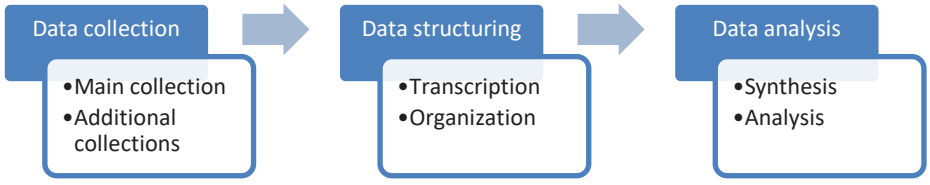

Fig. 1. Case study conduction overview

4 Results

As stated early, 9 case studies were conducted regarding the implementation of new technologies, which can be observed in Table 1. In relation to the synthesis of the results obtained for each case study for the Pettigrew's [11] strategic dimensions of context, process and content, they can be seen, respectively, in Tables 2, 3 and 4.

Table 1. Case studies overview

Case	Technology	Department
1	Machine vision system	Process engineering
2	Predictive maintenance	Maintenance
3	Data Matrix	Process engineering
4	Advanced Planning and Scheduling (APS)	Production Planning and Control
5	Data Matrix	Process engineering
6	Enterprise Resource Planning (ERP)	Production Planning and Control
7	Indoor geolocation	Process engineering
8	Business Intelligence (BI)	Quality
9	Photogrammetry	Quality

As observed in Table 1, nine case studies were conducted, being great part of them related to the adoption of technologies in the process engineering department. In addition, except for the case regarding the ERP adoption, all companies are classified as large companies according to the SEBRAE (*Serviço de Apoio às Micro e Pequenas Empresas*) classification [32].

The results obtained with the case studies, more specifically for the strategic dimension of *context* (Table 2), shows that great part of the demand for the technologies were related to legal aspects (3 cases), dependability (2 cases) and quality (2 cases). Regarding this legal demand for these cases, it is related to the demanded traceability of the process in order to obtain the ISO 9001 certification [33], being the cases 3 and 5 related to the maintenance of the certification by implementing traceability systems in their processes and the case 6 related to a small-sized company which are adopting an ERP system to further obtain the certification. Therefore, the demand for these cases could be also related to the quality and dependability since the ISO 9001 is a quality standardization and the traceability is related to the dependability of the process.

As for the context of the implementations, it can be observed that, except for the case 8, which were a personal initiative to implement a BI system, all the cases had an investment model based on a strategic management. However, even with this strategic management, it is also possible to observed that only the case 7 used a tax initiative existent in Brazil to promote innovation [34] in their strategic management and none of them informed about the uses of credit lines. In addition, it also can be noted that only few companies had a partnership in their development process, being only the cases 1, 2 and 7 supported by the academy. Therefore, even the companies having an innovation strategy, some initiatives that could also support the process are being misused.

Table 2. Case studies overview (Context)

Case	Outer context					Inner context		
	Macro environment	Sector	Suppliers	Demand criteria	Solutions	Technology access	Culture (Partners)	Investment model	Department (Leadership)
1	N/A	N/A	External (Partial)	Quality	3	Academy	Academy/ suppliers	Strategic management	Process
2	N/A	N/A	External (All process)	Dependability	1	Academy	Academy	Strategic management	Maintenance/ IT
3	Regulatory aspects	ISO / ABNT	External (Partial)	Legal	1	Partnership	None	Strategic management	Process
4	N/A	ISO / ABNT	External (All process)	Dependability	3	Supplier	None	Strategic management	PPC / IT
5	Regulatory aspects	ISO / ABNT	External (All process)	Legal	1	Partnership	Supplier	Strategic management	Process
6	Regulatory aspects	ISO / ABNT	External (All process)	Legal	5	Supplier	Consultant/ maintainer	Strategic management	Process
7	Tax incentives	ISO / ABNT	External (All process)	Cost	3	Supplier	Academy	Strategic management	New area
8	N/A	N/A	Internal	Speed	N/A	Intercompany	None	N/A	Responsibility of the sector
9	N/A	ISO / ABNT	External (All process)	Quality	3	Intercompany	None	Strategic management	Process

Table 3. Case studies overview (Process)

Case	Project		Resources			
	Methodology	Consequences	Financial	Human	Technological	Knowledge transference
1	Continuous planning	Experimentation	Process/ Product	Additional	Not formalized	Innovation	Informal training/ documentation
2	Own methodology	Traditional model	Process	Strategic	Formalized	Innovation	Informal training/ documentation
3	Partial project management	Traditional model	Product/ Process	Strategic	Formalized	Hybrid	Traditional training
4	Project management	Outsourced traditional model	Process	Strategic	Formalized	Innovation	Informal training/ documentation
5	Own methodology	Traditional model	Product/ Process	Strategic	Formalized	Hybrid	Traditional training
6	Project management	Experimentation	Product/ Process	Strategic	Formalized	Innovation	Informal training/ documentation
7	Own methodology	Traditional model	Process	Strategic	Formalized	Innovation	Traditional training
8	Continuous planning	Experimentation	Process	Additional	Not formalized	Innovation	Informal training
9	Own methodology	Traditional model	Process/ Product	Strategic	Formalized	Innovation	Traditional training

Table 4. Case studies overview (Content)

	Performance objectives (Influence)						Other (Influence)	
Case	Dependability	Cost	Flexibility	Quality	Speed	Ergonomics	Sustainability	Opportunities
1	Positive	Negative	-	Positive	Positive	Positive	-	Positive
2	Positive	Positive	Positive	-	Positive	Positive	Positive	Positive
3	Positive	Negative	-	-	Negative	Negative	-	-
4	Positive	Positive	Positive	-	Positive	Negative	Positive	Positive
5	Positive	Negative	-	-	Negative	Negative	-	-
6	Positive	Negative	-	-	Negative	Negative	Positive	Positive
7	Positive	Positive	Positive	-	Positive	Positive	Positive	Positive
8	Positive	-	-	Positive	-	-	Positive	Positive
9	Positive	Positive	Positive	Positive	Positive	Positive	Positive	Positive

Regarding the *process* of the implementations (Table 3), it can be observed that great part of the companies used different models of methodologies related to the project management, which were a significant factor for the success of the initiatives, since cases that do not used a formalized methodology, such as cases 1 and 8, did not had results as good as the other companies. However, even with the use of traditional methodologies, it is possible to observe that the use of agile methodologies, such as the Scrum [35], which could increase the speed of the process and, therefore, the returns of the technologies, are not being used.

In relation to the resources, as will be evidenced further with the analysis under Nicolini's [12] perspective, it is also possible to observe that other factors related to the success of the implementations are the human resources management and the budged forecast, since the cases 1 and 8, that did not used a formalized methodology or a formalized team for the implementation, had an impact on the effectiveness of the project. In addition, another aspect showed relevant to the success of the implementations were the knowledge management, since companies that adopted for informal trainings or that did not transferred the knowledge properly between the participants can have negative impacts after the implementations. This scenario was observed specifically in the case 1, where one of the teams responsible for the development of the solutions exit during the implementation process, and case 4, where the exit of the responsible for the process after the implementation resulted in a 6 month gap without the use of the system. However, as the case 4 had a formalized methodology, the knowledge could be reobtained and the system returned to operate normally, while in case 1, due to the lack of a formalized methodology and mainly the lack of financial resources and human management that made the team exit, resulted in a loss of knowledge. Therefore, a formalized methodology associated with a good resource's management is one of the main factors to the success of an implementation.

Regarding the *content* (Table 4), or the results obtained with the implementation, all the adoptions had a positive influence on the dependability of their process, which was already presented as one of the most influenced aspects by the implementation of new technologies by some studies [36, 37]. Conversely, cost and speed presented negative influences for several case studies. However, as can be observed in Table 4, the cases with these negative influences (1, 3, 5 and 6) are all related to legal and safety aspects of their products, being cases 3, 5 and 6 related to adoptions necessary for the ISO 9001 certification and case 1 related to the use of a machine vision system from improve product quality. Therefore, even these technologies having negative impacts in some performance objectives, they are still important for the companies to ensure the quality and safety of their products.

Finally, in relation to the other improvements, besides some negative influences in the ergonomic of some cases due to the reasons mentioned early, great part of the cases presented positive influences in the sustainability and opportunities. As for the ergonomics, the positive influences of the cases 1, 2, 7 and 9 are related to the automation of the process, reducing the activities necessary by the operators, while the negative influences, as stated early, are related to the increase of activities necessary by the operators in order to satisfy some legal objectives or to the implemented systems work properly. Regarding the sustainability, which is one of the main topics nowadays and

has been focus of several studies [38–43], 6 cases presented positive influences in this aspect, being them mainly related to the use of resources for operation (cases 2, 7 and 9), while the others were influenced for aspects such as the reduction of papers in the factory and of analysis systems (cases 4, 6 and 8). Finally, in relation to the opportunities, besides the cases related to the maintenance of the ISO 9001 certification, all cases presented a positive influence in this aspect, being great part of them related to the possibility to perform different analysis through the data collected and the possibility to adopt new systems and achieve new markets.

5 Protocol review

As stated early, another approach to evaluate the adoption of the new technologies are the five dimensions of practice proposed by Nicolini [12], which are considered as a more practical-based approach [12, 25]. Based on that scenario, this section aims at the understanding of the similarities and differences between both approaches: the strategic dimensions proposed by Pettigrew [11], which was the basis for present research and the construction of the case study protocol, and the dimensions of practice proposed by Nicolini [12].

For this comparison, a Quality Function Deployment (QFD) matrix was elaborated, where the information requirements of the used protocol were considered as being the quality characteristics and the dimensions of practiced proposed by Nicolini [12] as the demanded quality, aiming to understand which information requirements of the used protocol are considered the most relevant for the Nicolini's [12] approach [44]. In addition, it also should be noted that the QFD used for the present research was adapted for the present analysis, being all dimensions of practice considered equally relevant (same weight / importance) and without any correlation between the information requirements. Besides that, it also should be noted that, as the Nicolini's [12] approach involves only the understanding of the projects and the factors for its success, the information requirements regarding the strategic dimension of content were not included in the present analysis, since, as stated early, this dimension focuses in what were achieved by the implementation, which was not the focus of Nicolini's [12] five dimensions of practice and, therefore, the results for this strategic dimension would be considered as irrelevant for this approach. In relation to the results obtained with the QFD matrix, it can be observed in Table 5.

Table 5. Quality Function Deployment (Pettigrew x Nicolini)

	Context					Process					
	Outer context			Inner context		Project		Resources			
	Macro environment	Sector	Suppliers	Culture	Innovation strategy	Methodology	Consequences	Financial	Human	Technological	Knowledge transference
Work and efforts	O	O	Θ	Θ	Θ	Θ		Θ	Θ	Δ	Θ
Materially	Θ	Θ	Θ	Θ	Θ	Θ		O	O		O
Agency and creativity	O	O	O	Θ	Θ	O	Δ	Δ	O	O	O
Knowledge				Δ	Δ	O		Δ	O	Δ	Θ
Interests and power			Δ	Θ	O	O			O		Θ
Max relationship value	9	9	9	9	9	9	1	9	9	3	9
Weight / Importance	300	300	440	740	620	540	20	280	420	100	480
Relative Weight	7,1	7,1	10,4	17,4	14,6	12,7	0,5	6,6	9,9	2,4	11,3

Θ – Strong relationship (9) O – Moderate relationship (3) Δ – Weak relationship (1)

As observed in Table 5, the most relevant information requirements for the understanding of the projects under Nicolini's [12] approach were Culture, Innovation Strategy, and Methodology, which is also observed in related studies [45]. Conversely, the least relevant information requirements for the five dimensions perspective were Consequences and Technological resources.

Regarding the least relevant information requirements under Nicolini's [12] perspective, it can be observed that they were mainly associated with the goals of the projects and resources that do not directly involves communication and relations between the project participants for its management. Conversely, resources that demands the interaction between the participants to its management, such as Human resources and Knowledge resources, presented great relevance under a Nicolini's [12] perspective, which is also considered as relevant aspects for different models [46].

In relation to the most relevant information requirements under Nicolini's [12] perspective, it mainly involves the context of the company (inner context) and the methodology used to achieve their objective. Analyzing these results from a similar point of view as used for the resources, it can be observed that these three main information requirements under Nicolini's [12] perspective are also related to the communication and human resources management, since these aspects involves the relationship between the project participants and the people from outside of the organization, such as

suppliers, partners, stakeholders, academy, headquarters, etc. In addition, as observed in the case studies, a great strategy and the use of a proper methodology is also relevant for the effectiveness of the change, being the projects with a more consolidated innovation strategy and formalized project managements methodologies with the highest success rates [46].

Therefore, it is possible to observe that even the financial and technological resources being important for an implementation, the key factors for a more effective change is the integration and relationship between all the people involved in the project (employees, companies, suppliers, stakeholders, etc.). This scenario was observed in the case studies of the present research, since projects that did not had a formalized human resources management or a project management that included these integrations between the companies and the third parties involved in an early stage of the process, did not have the same level of success as the other companies who have done these predictions in the early stages of the process. In addition, consolidated innovation strategies and formalized project management methodologies are also key factors to increase the success rate of an implementation, being the highest successful implementations associated with projects that had formalized methodologies and a consolidated innovation strategy.

Finally, the analysis of the protocol under a Nicolini's [12] perspective allowed to identify that great part of the information collected using the Pettigrew's [11] strategic dimensions of *context*, *process* and *content* are also related to the Nicolini's [12] dimensions of practices, but analyzed from a different perspective, being the Pettigrew's [11] method associated to a more strategic point of view, englobing aspects that are not included in the other theories, such as the benefits and goals of the implementation, and the Nicolini's [12] framework associated to a more practical point of view, englobing aspects related to the key factors for a successful implementation, without approaching what was the objectives of the implementations.

6 Conclusion

Through the presented method, it can be said that the objective of support the understanding of what are the main success factors for implementing a new technology and what are the implications of these adoptions for the operations management was achieved, since several case studies regarding the implementation of new technologies could be performed and analyzed throughout different perspectives. it should be noted that the results presented in the case studies refer only to the scenario of the South and Southwest of Brazil, more specifically of the companies of the metal-mechanic and automotive sector, and may differ from other sectors or regions studied. Besides that, due to the pandemic scenario, some cases presented difficulties in the data collection, not being able to perform company visits or personal interviews.

In relation to the results obtained with the case studies, it was possible to identify that a good strategic plan and the use of a formalized methodology associated with a proper resources management are key factors for the effectiveness of an implementation. However, even with great part of the case studies having satisfactory results, some

other measures are still necessary to improve even more the performance of the implementations, being mainly related to the study of the macro environment of the company, since great opportunities as tax incentives and credit lines are not being used, and the development of agile methodologies for the implementation, since it was not observed for any of the companies and could help to improve the speed of the implementation processes and the benefits.

Regarding the analysis of the protocol under a Nicolini's [12] perspective, it allowed to identify that great part of the information collected using the Pettigrew's [11] strategic dimensions of *context*, *process* and *content* are also related to the Nicolini's [12] dimensions of practices. In relation to these similarities, they are mainly related to the understanding of the context of the organization and the used methodology, which were also observed in the case studies along with the human resources management as key factors for an effective implementation.

Therefore, using the information obtained with the case studies and the most relevant aspects under Nicolini's [12] perspective, it can be concluded that even the financial and technology resources being relevant factors for a successful implementation, the main factors for an effective implementation are not related to the resources available but the way that they are being managed and integrated. In relation to this scenario, it was also observed in the studies, where the companies that had a better strategy, using formalized methodologies, and a great relationship between the project participants and the third parties involved in the project presented the better results.

Finally, for future works, it is suggested to apply the proposed methodology to other regions and sectors related to the implementation of new technologies to analyze the differences between the applications in different scenarios. In addition, an analysis under other aspects, such as the batteries of change proposed by Prins et al [46] is also suggested.

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How do Industry 4.0 technologies impact performance objectives? Results of an empirical survey in large enterprises and SMEs of the Curitiba Metropolitan Region

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Abstract. Implications of Industry 4.0 for enterprises in general are still unclear. This paper examines how key technologies of Industry 4.0 impact production systems, more specifically performance objectives. The research method is based on a quantitative study carried out in Curitiba and Metropolitan Region with a focus on the metal-mechanic and automotive sectors. The results show which Industry 4.0 technologies have the highest implementation level and which technologies have the most impact on performance objectives. Furthermore, the presented survey provides not only a scenario of what the technologies being adopted are, but also a starting point for companies that are willing to invest in new technologies of what the possible benefits that they can possibly achieve are, based on what has already been adopted.

Keywords: Industry 4.0, production management, performance objectives.

1 Introduction

The fourth industrial revolution has been one of the most frequently discussed topics in the past few years [1]. This new technological revolution, also known as "Industry 4.0", has become publicly known in 2011 through a German government initiative called "Industrie 4.0" and was preceded by three other industrial revolutions that have driven dramatic increases in industrial productivity [2–6].

This revolution is based on new and radically changed technologies that aim at a fusion of the physical and the virtual world into cyber-physical systems (CPS) and attracted the interest of several studies, many related to the technologies being used, such as the Internet of Things (IoT) and computational techniques associated with large

volumes of data (Big Data Analytics) [1, 7–9]. However, the implications of these technologies to production systems is still unclear, since studies that formally discuss these implications are lacking, focusing excessively on the technologies without approaching their impact on management systems.

Based on this context, the present paper aims to support the understanding of how key technologies of Industry 4.0 are impacting production systems, more specifically performance objectives. For this, a survey was made with companies of the metal-mechanic and automotive industry of Curitiba Metropolitan Region, aiming to determine the overall implementation level of these technologies and their respective impacts on performance objectives [10, 11].

Therefore, the present paper is organized in four sections. In the following section, some concepts regarding the information used to the questionnaire construction are presented. After that, the research method used for the survey conduction and data processing is shown. Then, results and discussions regarding the implementation and improvement level results are presented. Finally, in the last section, conclusions obtained with the present research are drawn.

2 Theoretical Background

2.1 Industry 4.0 technologies

For the present research, six technologies associated with Industry 4.0 were selected based on their relevance in consulting reports and their use by companies of the target group (Curitiba Metropolitan Region) [4, 7, 12–15]. Regarding this selection, it was made taking the 27 technologies proposed by Brunheroto *et al*. [12] as a starting point and filtering them based on their number of appearances on five consulting reports (>3) and their number of uses by the companies of the target group (>10) on Brunheroto *et al.´*s [12] research.

After the filtering process, five technologies were obtained: Internet of Things, Cloud, Cybersecurity, Big Data Analytics and 3D Printing. However, due to the relevance of the Virtually Guided Self-Services on Brunheroto *et al.´*s [12] research, it was also included on the final set, even not being as cited as many times as the others in the consulting reports. Therefore, six technologies were selected to be used in the analysis of the impacts of their adoption on performance objectives: Internet of Things, Cloud, Cybersecurity, Big Data Analytics, Virtually Guided Self-Services and 3D Printing.

2.2 Performance objectives

Performance objectives describe what the manufacturing function should achieve in order to satisfy market requirements [10, 16–18]. About the definition of this set, many authors on operations strategy have their own set of performance objectives, and, therefore, no overall agreement exists on the terminology [10, 18]. Therefore, for the present research, the model proposed by Slack and Lewis [10] and Corrêa and Corrêa [11] was chosen, where five performance objectives are considered: dependability, cost,

flexibility, quality and speed. Regarding the definition of each topic, they can be observed in the following topics.

- **Dependability:** carrying out the work in a timely manner, abiding by the delivery commitments promised to the customers [19].
- **Cost:** carrying out the work in an inexpensive manner, producing goods and rendering services with a cost that enables them to properly perform, pricing for the market in a way that the organization revenue is also allowed for [19].
- **Flexibility:** changing what you do or the way the work is done, the ability to change or match the activities of operations to overcome unexpected circumstances or gain customers' unique behavior or introducing new products or services [19].
- **Quality:** performing tasks properly, procuring goods and services without error and in accordance with the previously-determined goals [19].
- **Speed:** performing tasks rapidly, minimizing the time between the customers' request for goods or services and the delivery [19].

3 Method

3.1 Study design

For the analysis of the main impacts of the adoption of Industry 4.0 technologies to production systems, more specifically the performance objectives, a survey was conducted with companies of the metal-mechanic and automotive sectors of Curitiba Metropolitan Region.

For this, the production system management model proposed by Slack and Lewis [10] and Corrêa and Corrêa [11] was taken as basis, which emphasize the strategic aspects of production systems management, since some companies' initiatives are being conducted in a strategic domain [20]. For the assessment of the Industry 4.0 technologies, as presented earlier, results from Brunheroto *et al.* [12] and five consulting reports were taken as basis [4, 7, 12–15]. Regarding the specific method for the present research, including the questionnaire construction and survey conduction, they will be further explained in the following topics.

3.2 Target group

As stated earlier, the target group for the present research was the Curitiba Metropolitan Region, more specifically from the metal-mechanic and automotive sectors. This target group was chosen due to the location of the university, which is sited in this region, and the economic relevance of this sector for the studied region [21].

Regarding the universe definition, it was made using a database, made available by FIEP (*Federação das Indústrias do Estado do Paraná*) [22], a civil society organization that serves as a hub for industry initiatives and partnerships in the selected area. In this database, filters were made based on the desired location and sectors, and 762 companies were found as the universe of companies for the present research.

3.3 Questionnaire construction

Once the universe of companies was defined, an online questionnaire was developed based on the information gathered in the theoretical background. Regarding the questionnaire, it consisted of a presentation section, four main sections and a last section referring to the feedback.

In relation to the four main sections, it aimed to present some concepts regarding the technologies and the performance objectives and to collect the data referring to the respondents, the implementation level of the six technologies and their respective improvement levels for all five performance objectives. For the implementation level questions, the respondent was asked to inform, in a level from 1 (we do not have) to 5 (we have advanced implementation), the implementation level of each one of the six technologies by their companies, similar to the model proposed by Frank *et al.* [23]. As for the improvement level questions, the respondent was asked to inform, in a level from 1 (none) to 5 (excellent), the improvement level provided by the used technologies in each one of the performance objectives, based on the responses of the previous sections.

3.4 Collection of responses

Once the questionnaire was constructed, they were sent mainly by e-mail to the whole universe previously mentioned and later resent to the companies with wrong contact information. After the questionnaire was sent to the entire universe, some other measures were made regarding possible restrictions on internet access by the companies, being the first one the rewrite of the questionnaire in document formats and the second one related to a warning e-mail, without any link or attachment, informing about the previous emails and the deadline for the responses.

3.5 Data processing

For the data processing, the responses were exported, briefly organized and sent to a BI (Business Intelligence) platform for the final processing and report generation. Regarding this report, it was divided in 3 main sections: Sample data, Implementation and Improvement and are explained below.

- **Sample data:** For the sample data section, pie charts regarding the companies' size and sector were constructed, as well as a map indicating the cities of the participant companies and graphs presenting the participation status, including the incomplete and complete responses, number of respondents and number of respondent companies.
- **Implementation:** The implementation section aims to analyze the implementation level of each technology. For this, pie and bar charts were respectively created to present the implementation level responses and the number of uses of each technology. Besides that, a table and a dispersion graph were also generated, aiming to

analyze the average implementation level and standard deviation for each technology across different sizes of companies.

- **Improvement:** For the improvement section, spider and boxplot graphs were constructed, as well as a table with the average improvement level and the standard deviation for each technology in each performance objective. In relation to the spider graph, it was created aiming to facilitate the visualization of which performance objective was more impacted by the adoption of each technology. Finally, regarding the boxplots and the table, they were generated to analyze the responses distribution and identify if the improvements are generally the same or if they have discrepancies according to different contexts of applications.

4 Results and discussion

For a better understanding of the present research, results are divided according to the report sequence presented previously, being presented first the sample data, followed by the implementation level and the improvement level results. In addition, an overview of the results regarding the implementation and improvement levels can be seen after the results in Figure 2.

4.1 Sample data

Using the method described previously, 76 responses from 63 companies were obtained, including 7 incomplete responses that could be used for the analysis. The size of the respondent companies according to SEBRAE (*Serviço Brasileiro de Apoio às Micro e Pequenas Empresas*) classification [24] can be seen on Figure 1.

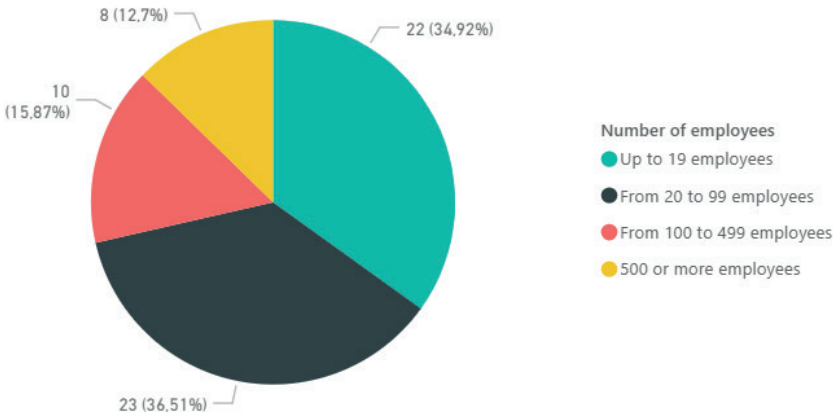

Fig. 1. Companies size (Curitiba Metropolitan Region)

As seen in Figure 1, great part of the respondents were from micro and small-sized companies, which represent more than 80% of the universe of companies in Curitiba Metropolitan Region. However, it also should be noted the number of responses from

large companies, which represent less than 5% of the universe and had a considerable response rate on this study [22]. Regarding to the reasons for this great diversity of sizes, it can be related to the interest regarding the subject (Industry 4.0), since it usually attracts more interest from companies that are trying to implement those technologies, which are usually the larger companies, and the easier access to larger companies throughout internal contacts and by the number of employees itself, since it has more possibilities of contacts inside the company.

4.2 Implementation levels

In relation to the implementation levels (Table 1), besides Cybersecurity, all technologies obtained an overall implementation level lower than 3, representing that great part of the companies from Curitiba and Metropolitan Region do not have any of the technologies presented in this study. These low overall implementation levels can be related to the sample, since, as stated earlier, a large number of responses were from micro (34,92%) and small (36,51%) companies (Figure 1), which can directly reflect on the overall results, since higher adoption levels are usually associated with larger companies, hypothesis that will be further evaluated through a Pearson correlation test. As for the overall implementation levels and their respective standard deviation obtained for each technology, they can be observed in Table 1.

Table 1. Average implementation levels

Pos.	Technology	Avg. Implem. level	St. dev.
1º	Cybersecurity	3,04	1,72
2º	Virtually Guided Self-Services	2,44	1,55
3º	Cloud	2,41	1,55
4º	3D Printing	2,14	1,47
5º	Big Data Analytics	2,06	1,26
6º	Internet of Things (IoT)	1,96	1,20

As observed in Table 1, the highest overall implementation level was associated with Cybersecurity (3,04), while the lowest levels were associated with Internet of Things (1,96) and Big Data Analytics (2,06). This is due to two main reasons: necessity and complexity, since technologies such as Cybersecurity are usually necessary to increase the security and reliability of the company and, therefore, can be considered a necessity for those companies that are willing to adopt digital technologies to prevent them from cyberattacks. Conversely, Big Data Analytics and Internet of Things are not a necessity for companies of all sizes, since they usually aim to improve the process and do not have a direct demand in terms of security and legislation, and are usually more complex to implement than other technologies, since they usually need the support from other technologies for their correct operation.

Table 2 shows the results obtained for each technology by the companies' size, as well as their respective correlation level between the average implementation levels and

companies' size. Regarding the correlation level results, the coefficients were calculated considering the implementation levels responses for each size of company and the companies' size in a level from 1 to 4, being level 1 associated with the micro-sized companies and level 5 with large companies.

Table 2. Average implementation levels per size and correlation

Pos.	Technology	Micro	Small	Medium	Large	r (corr.)
1º	Cybersecurity	1,80	2,96	3,27	4,79	0,60
2º	Virtually Guided Self-Services	1,52	2,35	2,82	3,77	0,51
3º	Cloud	1,48	2,29	2,73	3,85	0,53
4º	3D Printing	1,47	1,64	2,00	3,85	0,57
5º	Big Data Analytics	1,57	1,83	2,00	3,31	0,45
6º	Internet of Things (IoT)	1,43	1,64	2,09	3,31	0,54

As observed in Table 2, there is a positive correlation between companies' size and the implementation, since all technologies presented a positive Pearson correlation coefficient between their implementation levels and the companies' size, being 0,45 the lowest coefficient. Therefore, the low overall implementation levels presented in Table 1 are indeed related to the sample, as stated earlier, and not a reality for all sizes of companies, being the results for the large companies higher in comparison to companies of other sizes, as can be observed in Table 2.

Regarding the results by companies' size (Table 2), the overall implementation level of the technologies for large companies is high, being all levels higher than 3, representing that most of the companies have at least an implementation project under development. In relation to the highest implementation level for large companies, it is associated with Cybersecurity (4,79), which has an advanced implementation in most part of the companies. Conversely, Big Data Analytics (3,31) and Internet of Things (3,31) presented the lowest levels for large companies, which can be related to the complexity issues mentioned earlier.

As for SMEs, Cybersecurity also presented the highest implementation level among all technologies for micro (1,80), small (2,96) and medium-sized companies (3,27). As for the lowest implementation levels, it is associated with the Internet of Things for micro-sized companies (1,43), 3D Printing and Internet of Things for small-sized companies (1,64) and Big Data Analytics and 3D Printing for medium-sized companies. In addition, it should be noted that, even these technologies presenting the lowest average implementation levels, some of these averages can be considered statistically equal to other technologies, which can be observed mainly for the micro-sized companies, and, therefore, there is no clear definition regarding the lowest implementation levels.

4.3 Improvement levels

In relation to the improvement levels (Table 3), the overall improvement levels were, in general, higher than 3, representing that the companies had at least a good overall improvement by adopting the studied technologies. Regarding these overall implementation levels, they were calculated as the average of the implementation levels for all performance objectives (dependability, cost, flexibility, quality and speed) and, therefore, technologies that have a higher overall implementation level also tend to have a high average improvement level for all performance objectives.

Table 3. Average improvement levels (General)

Position	Technology	Avg. Improv. level	St. dev.
1º	3D Printing	3,50	0,97
2º	Internet of Things (IoT)	3,35	0,82
3º	Cybersecurity	3,34	1,12
4º	Cloud	3,18	0,91
5º	Virtually Guided Self-Services	3,17	1,04
6º	Big Data Analytics	3,06	0,90

As observed in the general ranking of technologies (Table 3), the 3D Printing presented the highest overall improvement level (3,50), while the lowest was associated to the Big Data Analytics (3,06). However, as will be discussed further, the overall improvement level does not necessarily represent what the best technology is in terms of improvement, since it can vary according to the context of application. Therefore, the results presented in this section aim to support the understanding of what improvements can be achieved by adopting these technologies, and what technology has a better improvement potential for each of the performance objectives.

In addition, it also should be noted that, even the Big Data Analytics having presented the lowest overall improvement level, some technologies, such as the Internet of Things, are still necessary to enable its full potential and, therefore, its performance may have been influenced by the low adoption rate of the Internet of Things.

In relation to the technology rankings for each of the performance objectives (dependability, cost, flexibility, quality and speed), they can be observed, respectively in Tables 4, 5, 6, 7 and 8.

Table 4. Average improvement levels (dependability)

Position	Technology	Avg. Improv. level	St. dev.
1º	Cybersecurity	3,81	1,05
2º	Internet of Things (IoT)	3,64	0,67
3º	3D Printing	3,50	0,65
4º	Virtually Guided Self-Services	3,39	1,16
5º	Cloud	3,38	1,01
6º	Big Data Analytics	3,07	0,83

As observed in Table 4, the Cybersecurity presented the highest average improvement level for dependability (3,81), while the lowest level was associated with Big Data Analytics (3,07). Regarding the reason for this ranking, as stated earlier, the low improvement level of Big Data Analytics could be related to the low adoption rate of the Internet of Things, since this technology is used to collect the data for the analysis and, therefore, a lack of an automatic gathering system can result in a bad input for the Big Data Analytics and, consequently, a bad analysis (output).

In relation to cybersecurity, as expected, it presented the main improvements in the dependability of the process, since, as stated earlier, it is a technology that usually aims at this objective by improving the security of the company. However, it also should be noted that the Internet of Things and 3D Printing also had good results in terms of average improvement levels for Dependability and mainly in terms of standard deviations, which were the lowest for this ranking, representing that they had a good performance for different contexts of applications.

Table 5. Average improvement levels (cost)

Position	Technology	Avg. Improv. level	St. dev.
1º	3D Printing	3,29	1,38
2º	Internet of Things (IoT)	3,18	0,87
3º	Big Data Analytics	3,07	0,83
4º	Virtually Guided Self-Services	3,00	1,04
5º	Cybersecurity	2,95	1,08
6º	Cloud	2,83	0,82

As observed in Table 5, 3D Printing presented the highest average improvement level for cost (3,29), while the lowest level was associated with Cloud (2,83), which is also the lowest score among all performance objectives and technologies. However, it should be noted that, even this technology having presented the highest average improvement level for cost (3D Printing), it did not present an improvement level as high as observed in other rankings, being the only ranking where all technologies presented an average improvement level under 3,5, representing that cost is not the main goal of the studied technologies.

In addition, it should also be noted that, even the 3D Printing having the highest average improvement level, it also presented the highest standard deviation of all rankings, representing that even the technology with the most improvement in terms of cost can perform differently according to its context of application.

Table 6. Average improvement levels (flexibility)

Position	Technology	Avg. Improv. level	St. dev.
1º	3D Printing	3,86	0,86
2º	Cloud	3,29	1,00
3º	Internet of Things (IoT)	3,09	0,94
4º	Virtually Guided Self-Services	3,09	1,08
5º	Cybersecurity	2,97	1,01
6º	Big Data Analytics	2,86	0,86

As observed in Table 6, the 3D Printing presented the highest average improvement level for flexibility (3,86), which is also the highest score among all performance objectives and technologies, while the lowest level was associated with Big Data Analytics (2,86). Regarding this result, the goal of the technologies can explain this ranking, since 3D Printing is usually used to improve the flexibility of the manufacturing process or to support the development process, which intrinsically demands high flexibility. Conversely, Big Data Analytics and Cybersecurity usually aim to improve other aspects of the production system and, therefore, are understandable to have lower levels compared with the other technologies, besides the fact already explained regarding the additional technologies necessary to enable the full potential of Big Data Analytics.

In addition, it should also be noted that 3D Printing, besides the highest improvement level, also has the lowest standard deviation, representing that its great performance was not exclusive for some context of applications.

Table 7. Average improvement levels (quality)

Position	Technology	Avg. Improv. level	St. dev.
1º	Cybersecurity	3,62	1,11
2º	Internet of Things (IoT)	3,55	0,82
3º	3D Printing	3,36	0,74
4º	Cloud	3,29	0,81
5º	Virtually Guided Self-Services	3,26	1,01
6º	Big Data Analytics	3,14	1,03

As observed in Table 7, the Cybersecurity presented the highest average improvement level for Quality (3,62), while the lowest level was associated with Big Data Analytics (3,14). Regarding this ranking, the high position of Cybersecurity can be explained by the association that people usually make with security, reliability,

dependability and quality, since both rankings (Tables 4 and 7) presented similar results. Therefore, as the results were very similar, the comments made for the dependability ranking are also applied for the present ranking, where the Internet of Things and 3D Printing presented the lowest standard deviations and, therefore, presented a great performance throughout different contexts and the low performance of Big Data Analytics can be associated with the low adoption of its supporting technologies.

Table 8. Average improvement levels (speed)

Position	Technology	Avg. Improv. level	St. dev.
1º	3D Printing	3,50	1,09
2º	Cybersecurity	3,32	1,11
3º	Internet of Things (IoT)	3,27	0,79
4º	Big Data Analytics	3,14	1,03
5º	Virtually Guided Self-Services	3,13	0,92
6º	Cloud	3,08	0,88

As observed in Table 8, 3D Printing presented the highest average improvement level for speed (3,50), while the lowest level was associated with Cloud (3,08). However, even with the high improvement level of speed for 3D Printing, it also presented a high standard deviation, representing that its application can perform differently according to the context. Regarding the reason for this high standard deviation, it can be associated with the two main applications of this technology: manufacture and development, since the manufacture process usually demands a higher speed than in a prototyping process and, therefore, the adoption of the technology in this context could not provide an improvement as good as in a development context.

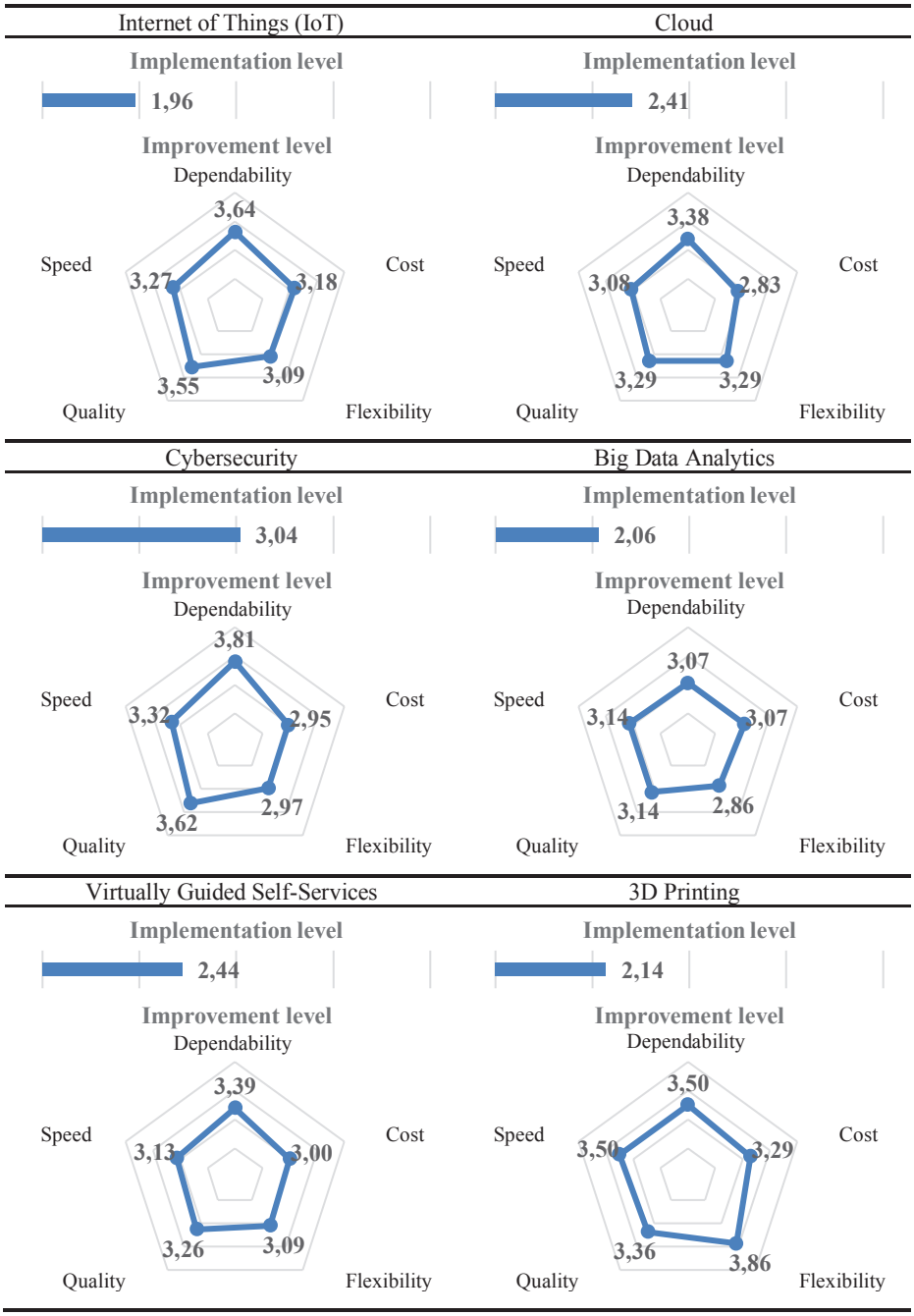

Fig. 2. Results overview

5 Conclusion

Through the presented method, it can be said that the objective of analyzing the main impacts of the Industry 4.0 technologies to the production systems was achieved, since a survey of companies of Curitiba and Metropolitan Region regarding the overall implementation level and their implication to the performance objectives could be performed. However, it should be noted that the results presented refer only to the scenario of the Curitiba Metropolitan Region, more specifically of the companies of the metal-mechanic and automotive sector and may differ from other sectors or studied regions.

As presented in the topic of results and discussion, the overall implementation level of the Industry 4.0 technologies of companies in Curitiba and Metropolitan region is low, representing that great part of the companies do not have any of the studied technologies. In addition, it also should be noted that an increase of the implementation levels according to the companies' size was observed, being the results for the large companies significantly higher comparing to other sizes of companies, representing that great part of the technologies adopted in the studied region are located in large companies. Regarding the adoption patterns, throughout the ranking presented in Table 1, was possible to identify that the technologies are being adopted mainly in terms of its necessity and complexity, being fundamental technologies for security, such as Cybersecurity, the most implemented, while more complex technologies, such as Internet of Things and Big Data Analytics, the least implemented technologies.

In relation to the improvement levels, the dependability and quality were the most improved aspects by the implementation of the technologies, which is congruent with the results obtained in previous researches related to the most considered performance objectives for technologies adoption [12]. Regarding the technologies, the 3D Printing (3,50) and the Internet of Things (3,35) presented the highest overall improvement levels, being both in the top 3 of improvements for all performance objectives. However, it should be noted that the overall improvement level results do not necessarily represent what are the best technology in terms of improvement, since the results can vary according to the context of application, which was observed with 3D Printing, that presented the highest average improvement level for cost and speed, but also one of the highest standard deviations, representing that its performance strongly depend on the context of application. Therefore, the results regarding the improvement levels, aims to support the understanding of what improvements can be achieved by adopting these technologies and what technology has a better improvement potential for each of the performance objectives based on what has been adopted by the companies of the present study.

Furthermore, it can be concluded that even with the constant adoption of Industry 4.0 technologies, the implementation levels are still low, being great part of the technologies still concentrated in the larger companies. Regarding the improvement levels, it could be observed that not all technologies have the potential to improve all the performance objectives like the Internet of Things and, if they have, the results can vary according to the context of the application, as observed with 3D Printing.

Finally, for future works, it is suggested to apply the proposed method to other regions and sectors to analyze the differences between the applications in different

scenarios. In addition, case studies are also suggested related to these adoptions, aiming to understand how that adoption occurred and the reasons for differences between regions, since there is other factors to be considered (management, internal capacities, human resources, infrastructure, interoperability, etc.) that could impact on the technologies implementation and performance, as observed in other studies [25–30].

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Transformação digital na prestação de serviços: mapeamento de tecnologias

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Resumo. O presente artigo tem como objetivo mapear as tecnologias, em especial as relacionadas à transformação digital e por consequência à Indústria 4.0, que têm sido implementadas nas operações de serviços. A análise buscou identificar, além de qual tecnologia era utilizada/estudada, questões como qual o contexto em que foi aplicada, qual problema ela pretende solucionar e qual o tipo de serviço em que é aplicada. Para atender ao objetivo supramencionado, foi realizada uma revisão sistemática da literatura, composta pelas etapas de definição das bases de dados e termos e critérios de busca, busca dos estudos, eliminação de duplicados e seleção dos estudos. Assim, no portfólio de 10 artigos selecionados por meio da revisão, foram encontradas aplicações de tecnologias mais básicas, como sistemas de gerenciamento, até tecnologias mais complexas e que integram a chamada Indústria 4.0, como *Cloud Computing*, Internet das Coisas e *Blockchain*. Infere-se, através dos estudos, que as aplicações das tecnologias são realizadas com maior foco em serviços que possuem alta quantidade de informações, o que dificulta sua análise e armazenamento, e em serviços que requerem mais informações do que as disponíveis pela organização. Como contribuição da pesquisa tem-se a demonstração da possibilidade da aplicação de diversas tecnologias nas operações de serviços, com finalidades individuais diferentes e que têm sido aplicadas com frequência na indústria, e que podem trazer diversos benefícios para a prestação de serviço.

Palavras-chave: Tecnologia, Transformação Digital, Operações de serviços.

1 Introdução

A moderna indústria de serviço tornou-se uma das principais fontes de crescimento econômico mundial na maioria dos países. Uma convergência de circunstâncias tem levado as funções de Tecnologia da Informação a se tornarem mais orientadas a serviços para um melhor alinhamento com os objetivos das organizações. Exemplo disso é que as operações de serviço passaram a abranger questões como comércio eletrônico B2B, educação digital e medicina digital [1, 2].

Essas tendências geram para os setores responsáveis pela TI, tanto por parte do setor público quanto do privado, uma crescente pressão para que operem com uma base mais econômica. Também geram uma crescente dependência de informações quase em

tempo real para apoiar atividades de caráter crítico, uma necessidade de integridade de relatórios para fins de atender requisitos regulatórios mais rigorosos, e demandas mais exigentes para redução no nível de tolerância e falha na infraestrutura de TI [2].

Considetando que a engenharia empresarial é um campo de estudo multidisciplinar, que envolve conhecimento de diversas áreas, a exemplo de ciência organizacionais e tecnologia da informação [3], e tendo em vista as questões apresentadas, este artigo tem como objetivo mapear as tecnologias digitais que têm sido implementadas nas operações de serviços, com foco em identificar questões como: qual o contexto em que a tecnologia foi aplicada, qual problema ela pretende solucionar, e qual o tipo de serviço em que é aplicada.

Além desta seção introdutória, este artigo está estruturado com seções que abordam o referencial teórico necessário para o alcance do objetivo, com uma seção que aborda os aspectos metodológicos utilizados na elaboração deste estudo, e com as seções que apresentam os resultados alcançados. Finalmente, a última seção apresenta as considerações finais, sugestões de pesquisa e contribuições deste estudo.

2 Transformação digital

As tecnologias digitais têm se mostrado como um novo núcleo vital das economias modernas. Países líderes têm se posicionado de forma estratégica em relação ao tema, perante o qual governos, academia e indústrias têm se esforçado para antecipar o ritmo e a escala com que esses avanços mudarão a maneira como o mundo funciona, assim como para identificar e alavancar as oportunidades e enfrentar os desafios que esses avanços trarão [4, 5].

De forma holística, a transformação digital pode ser entendida como “as mudanças que a tecnologia digital causa ou influencia em todos os aspectos da vida humana” [6, p. 689]. No âmbito organizacional, pode ser definida como “o uso de tecnologia para melhorar radicalmente o desempenho ou o alcance das empresas” [7, p. 1]. Em suma, pode ser entendida como os efeitos combinados de várias inovações digitais que produzem novos atores, estruturas, práticas, valores e crenças, os quais mudam as regras existentes no contexto das organizações, ecossistemas e indústrias [8].

Algumas das principais tendências da transformação digital das empresas possuem relação com a digitalização de produtos e serviços, por meio da qual os produtos e serviços são enriquecidos com serviços de valor agregado ou completamente digitalizados; com a digitalização do trabalho, o que facilita o trabalho em conjunto a grandes distâncias; e com a digitalização de modelos de negócios, uma vez que as empresas precisam repensar em seus negócios para desenvolver modelos inovadores de acordo com as habilidades e competências dos funcionários [9].

A manufatura digital, conjunto de tecnoloigas utilizadas para o gerenciamento de informação que auxiliam na tomada de decisão em todo o ciclio de vida de um produto, vem ganhando cada vez mais importância no cenário de base tecnológica como uma área de conhecimento da chamada Indústria 4.0 [10].

Esse termo foi apresentado pela primeira vez em 2011, por meio de um artigo do governo da Alemanha para designar um conjunto de estratégias de alta tecnologia para 2020. Atualmente, o termo Indústria 4.0 tem sido utilizado para descrever uma nova revolução industrial, que se baseia na integração de tecnologias da informação e

comunicação e da tecnologia industrial, bem como na construção de sistemas cyber-físicos com o objetivo de tornar as fábricas digitais e inteligentes [11].

Alguns dos principais recursos relacionados à Indústria 4.0 dizem respeito à capacidade em tempo real, interoperabilidade, e integração horizontal e vertical de sistemas de produção através de tecnologias de informação e comunicação [12]. Envolve tecnologias como Internet das Coisas (IoT), serviços em nuvem, *Big Data* e *analytics*, que, dentre outros, permitem a coleta e análise de dados em tempo real, fornecendo informações úteis ao sistema de fabricação, e que compõem o chamado sistema cyber-físico [13]. Além dessas, pode-se citar ainda tecnologias como *Blockchain* e realidade aumentada [5].

3 Serviços

Gerenciar serviços é uma tarefa diferente de gerenciar a produção de bens, isso porque os serviços possuem características especiais em comparação à gestão da manufatura. A classificação tradicional de bens e serviços determina quatro principais diferenças: perecibilidade, sendo os serviços perecíveis e os produtos, por durarem um período de tempo, menos perecíveis; intangibilidade, sendo os serviços intangíveis e os produtos tangíveis; heterogeneidade, característica pertencente aos serviços, tendo em vista que cada serviço é prestado de forma diferente para cada cliente, enquanto os bens físicos são mais homogêneos, e inseparabilidade entre produção e consumo, sendo que os serviços são produzidos e consumidos simultaneamente, enquanto os bens físicos são produzidos para posteriormente serem consumidos [14].

No entanto, a importância dos serviços para as organizações varia de acordo com alguns fatores, sendo muito difícil que uma empresa não possua atividades de serviços, seja como atividade-fim principal ou complementar, ou como atividade de apoio interno. Os serviços podem desempenhar quatro diferentes papéis dentro de uma organização: 1) serviço como atividade principal da empresa, prestado diretamente ao cliente; 2) como diferencial competitivo em empresas de manufatura, os quais complementam os produtos criados pela empresa e agregam valor ao cliente, mas que não geram receitas significativas; 3) como centro de lucro para empresas de manufatura, os quais complementam os produtos, agregam valor ao cliente assim como geram receitas e lucro para a empresa; e 4) serviços como atividade interna da empresa, prestados aos clientes internos [14].

4 Metodologia da pesquisa

Para o alcance do objetivo do estudo – mapear as tecnologias que têm sido implementadas nas operações de serviço, em especial as tecnologias que caracterizam a chamada transformação digital, optou-se pela realização de uma revisão de literatura, isso porque, fundamentalmente, o avanço do conhecimento deve ser construído com base em trabalhos anteriores existentes. A revisão deve ser válida, confiável e repetível [15].

Assim, a fim de atender a esses critérios, a revisão de literatura desta pesquisa consistiu em: 1 – definição das bases de dados e termos e critérios de busca; 2 – busca

dos estudos; 3 – eliminação de duplicados e 4 – seleção dos estudos, composta por três sub-etapas: leitura do título, leitura do resumo e por fim, leitura do documento na íntegra. Em relação à primeira etapa do método, foram definidos os critérios de busca conforme apresentado na Quadro 01:

Quadro 01 – Critérios de busca

Critérios de busca		
Base de dados	*Scopus*	*Web of Science*
Tipo de documentos	Não limitado	
Ano	Não limitado	
Termos de busca (em título, resumo, palavras-chave e tópico)	*"service management" / technolog* / digital*	
Operadores	*AND*	
Idioma	Não limitado	
Pesquisa no banco de dados		
"service management" AND technolog AND digital*		
Resultados		
Portfólio inicial	127	37
Sem duplicados	137	
Portfólio final	09	

Fonte: Elaborado pelos autores (2020).

Para a busca dos artigos, realizada em meados de dezembro de 2019, foram selecionadas as bases de dados Scopus, por ser considerada o maior banco de dados de resumos e citações da literatura com revisão por pares: revistas científicas, livros, processos de congressos e publicações do setor [16], e a base Web of Science, por justificativa semelhante, considerando a abrangência desta base ao fornecer acesso a cerca de 12 mil períodos, de todas as áreas do conhecimento [17].

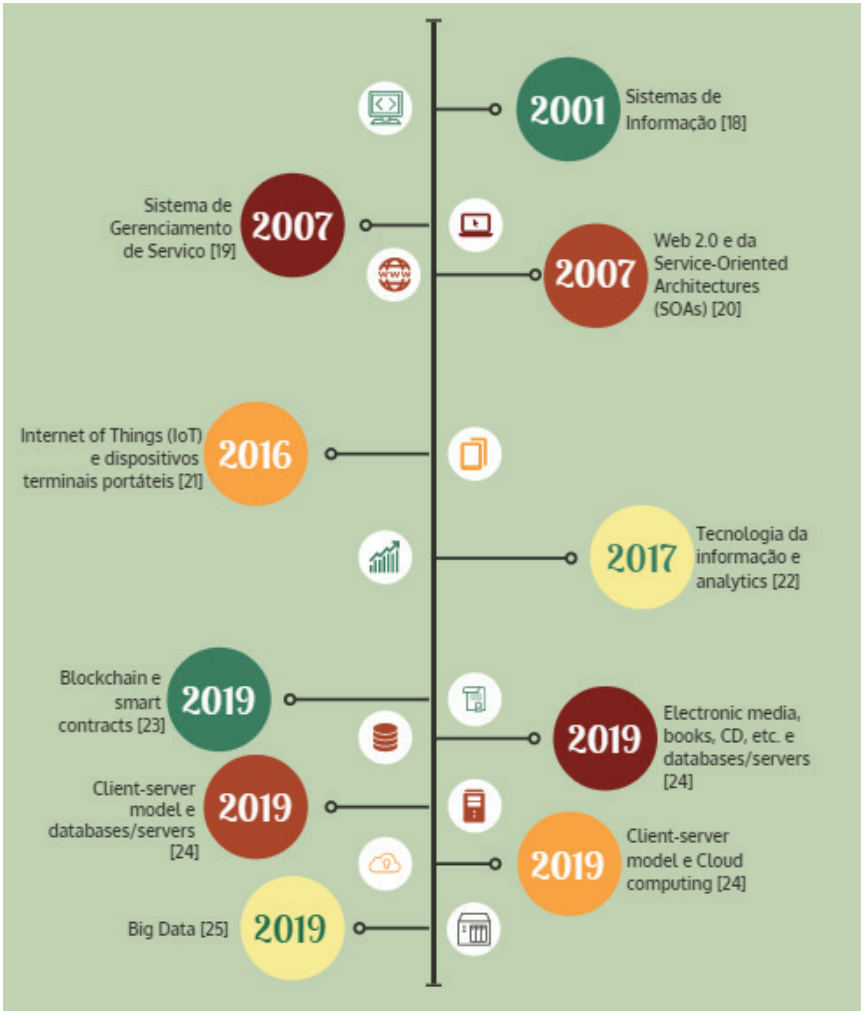
O Quadro 01 também apresenta os resultados das buscas. De um portfólio de 137 artigos não duplicados, foi possível obter, após a filtragem pela leitura dos títulos, pela leitura do resumo e por fim, pela leitura integral dos estudos que passaram pelos filtros anteriores, um portfólio de 09 artigos. Para a seleção dos artigos, seguindo os passos descritos, foram levados em consideração artigos que continham em seu conteúdo o estudo da aplicação de uma tecnologia de informação e comunicação com fins a proporcionar solução a problemas ou melhorias na prestação de algum serviço.

Os artigos que compõem o portfólio obtido com a aplicação do método foram analisados, por meio de análise de conteúdo, com vistas a identificar questões como: qual a tecnologia utilizada/estudada; qual o contexto em que foi aplicada, qual problema ela pretende solucionar, quais problemas ainda precisam ser solucionados, e qual o tipo de serviço em que é aplicada. Porém, nem todos os artigos disponibilizavam todas as informações desejadas, e as informações disponíveis são expostas na seção a seguir.

5 Resultados e discussões

O relacionamento entre TI e operações de serviços não é recente, e embora tenha se intensificado com o advento da chamada Transformação Digital, sistemas de gestão de serviços baseados em tecnologia da informação já vinham sendo usados há algum tempo. A Figura 01 busca apresentar um histórico do estudo de tecnologias aplicadas aos serviços. Os dados que compõem a figura foram extraídos dos artigos do portfólio, sendo a representação temporal baseada no ano de publicação do artigo, e as tecnologias, o que o respectivo artigo estuda ou apresenta como tecnologia.

Figura 01: Tecnologias estudadas para aplicação nas operações de serviços com base no ano do estudo



Fonte: Elaborado pelos autores (2020).

Com isso é possível verificar que no início dos anos 2000 a área de tecnologia da informação já era estudada como forma de auxiliar, por meio de sistemas, o gerenciamento de serviços, evoluindo para a aplicação de tecnologias mais complexas ao final da segunda década, a exemplo do *Blockchain* e *Cloud Computing*. Assim, conforme apresentado na Figura 01, a primeira tecnologia identificada no portfólio foi o Sistema de Informação no contexto da enfermagem. Neste, [18] descrevem o desenvolvimento e a avaliação de um Sistema de Informação para a Administração de Serviços de Enfermagem que classifica todas as informações relacionadas ao pessoal de enfermagem e ajuda a administração a lidar com os dados de enfermagem apropriados [18].

A segunda tecnologia apresentada refere-se à um Sistema de Gerenciamento de Serviços. Em 2007, com o objetivo de atender a todos os requisitos necessários para criar um sistema de governo eletrônico em torno dos cidadãos e alcançar a população o máximo possível para superar o fosso digital em territórios e comunidades em desvantagem, [19] apresentam um Sistema de Gerenciamento de Serviços.

Os principais problemas enfrentados por comunidades desfavorecidas (na Itália) frente à necessidade de interação com as administrações públicas e os governos, eram questões relacionadas à burocracia, procedimentos ambíguos, desintegração funcional, estruturas de autoridades vagas e/ou sobrepostas, e fragmentação de informações [19].

Porém, no que tange a prestação de serviços eletrônicos pelo governo italiano, onde a pesquisa teve seu foco, e o desenvolvimento de ofertas integradas de serviços administrativos, a Itália promovia um processo para renovar o setor de Administração Pública (AP) usando tecnologias de TIC para reduzir custos e melhorar a satisfação dos cidadãos e das empresas, e embora, em alguns casos, tenham sido introduzidas soluções interessantes e inovação tecnológica, vários problemas ainda estavam em aberto, a exemplo da padronização das tecnologias envolvidas, à interoperabilidade entre diferentes administrações públicas, e a introdução de soluções econômicas [19].

Para amenizar alguns desses problemas, os autores apresentam uma arquitetura composta por um repositório, o qual contém o catálogo de serviços e centraliza as informações. Cada Services Management System, como por exemplo, o sistema do governo eletrônico federal, estadual e municipal, operam de forma independente, mas exploram o mesmo catálogo e, em seguida, usam os mesmos serviços [19].

Também em 2007, [20] busca por meio de seu estudo contrastar a internet da época com a internet de serviços prevista, sob a perspectiva de três categorias: partes interessadas, aplicativos e tecnologia. Por meio do artigo, o autor elabora como os princípios e tecnologias da Web 2.0 e da Service-Oriented Architectures (SOAs), podem ser usados para facilitar o surgimento de uma "SOA global". O autor propõe uma arquitetura de referência da Internet dos Serviços (IoS), que considera a Internet como uma plataforma global para a recuperação, combinação e utilização de recursos interoperáveis. Essa Internet de última geração permitirá que usuários e empresas privadas colaborem sem problemas através do uso de serviços eletrônicos interoperáveis e, assim, impulsionar a industrialização de serviços intensivos em informações [20].

Em 2016, a temática de aplicação de tecnologias digitais e prestação de serviços foi abordada por [21]. Neste, os autores apontam que o turismo rural desempenha um papel cada vez mais importante na proteção cultural, desenvolvimento econômico, aumento da renda dos agricultores e desenvolvimento rural sustentável. Porém, apresenta alguns

problemas como pontos cegos no canal de serviço, conteúdo de serviço unilateral simples e prestação de serviços passiva, assim como as aplicações de tecnologia nesse tipo de serviço são muito restritas e apresentam problemas nos seguintes aspectos:

- os canais de serviço não são suficientes: como as fazendas geralmente são muito grandes, é difícil e demorado fornecer serviços pelos métodos tradicionais, gerando possíveis pontos cegos;
- é difícil obter o conteúdo do serviço: há muitos tipos de informações em uma fazenda, como nomes de vegetais, métodos de plantio, métodos comestíveis, ambiente de crescimento e assim por diante. Mesmo perguntando às equipes de serviço, a resposta geralmente é simples, unilateral e falta de confiabilidade científica razoável;
- os serviços são fornecidos apenas nos métodos passivos: o serviço vem das demandas dos consumidores, como informações, compras e entretenimento. Isso significa que se não há demandas, não há serviço. Esse tipo de método de serviço é passivo, único e falta de individualidade e serviço de iniciativa.

Para auxiliar na resolução dessas questões, os autores [21]. propõem um sistema chamado Intelligent Entertaining Farm Management System (IEFMS), que tem como base a *Internet of Things* (IoT) e dispositivos terminais portáteis.

Em suma o sistema possibilita:

- (1) Gerenciamento dinâmico digital: onde, com base em uma variedade de aplicações da tecnologia IoT, é possível atingir o monitoramento em tempo real do ambiente das fazendas, promovendo gerenciamento de inovação em tecnologia agrícola, e permitindo analisar as preferências dos passeios de acordo com os dados coletados das ações dos turistas;
- (2) Serviços ativos e personalizados: atendendo às necessidades de usuários individuais, é possível alcançar experiências, processos e monitoramento personalizados, usando a tecnologia de identificação pessoal e a política de acesso. Para isso, serviços de exibição de recursos de informação, mensagens de texto e serviços de envio ativo de jornais móveis foram fornecidos de acordo com o processo de personalização do usuário, usando dispositivos de IoT;
- (3) Modo Experiência Multidimensional: com base no serviço de informações multimídia e nos traços do serviço de localização, é proposto um modo de experiência multidimensional desenvolvido com base em uma grande quantidade de recursos de informação, como vídeo, áudio, imagens, texto, localização turística, pista de turismo e assim por diante [21].

Em 2017 um exemplo de estudo que aborda as temáticas aqui estudadas foi desenvolvido por [22]. Tendo em vista a crescente população de pacientes em todo o mundo e a crescente demanda por serviços de saúde de alta qualidade, o que tem imposto severas restrições de capital, recursos e capacidade humana aos hospitais, a adoção de serviços de internação que visam melhorar o planejamento de fluxos de trabalho em todo o hospital usando técnicas de tecnologia da informação (TI), gerenciamento de operações (OM) e análise avançada de dados (DA) tem sido identifica com frequência na prestação de serviços de saúde.

Considerando este contexto, [22] propõem uma bancada digital unificada para ajudar várias partes interessadas a melhorar o planejamento e a alocação de escassos recursos hospitalares, a fim de melhorar a transparência e a eficiência dos serviços de internação. A plataforma utiliza tecnologia da informação, gerenciamento de operações e análise de dados para apoiar não apenas os tomadores de decisão da área de saúde, mas também

especialistas em análise e sistemas de informação da área de saúde, bem como educadores desses tópicos.

Em 2019, tendo em vista o fato de que o banco digital, como um serviço essencial, pode ser difícil de acessar em regiões rurais remotas, onde a conectividade de rede está indisponível ou intermitente, [23] propõem um esquema de pagamento digital baseado em *Blockchain* que pode fornecer serviços confiáveis sobre redes não confiáveis em regiões remotas, considerando um cenário em que exista uma estação base administrada pela comunidade e que fornece conectividade de rede local confiável, enquanto se conecta intermitentemente à Internet mais ampla.

Os autores [23] propõem implementar cadeias de blocos para processamento de transações, tendo em vista que elas podem ser operadas por indivíduos sem nenhuma autoridade centralizada. Ainda, o cenário proposto se encaixa nas condições de uma *Blockchain* com permissão pública. Para rastrear e gerenciar a operação do sistema, os operadores de pagamento criam um Contrato Inteligente para registrar tipos de contas, saldos de usuários tanto na moeda fiduciária quanto na moeda Token, além de distribuir recompensas de mineração.

Ou seja, por meio da proposição dos autores, aproveitam-se as garantias de verificação distribuída da tecnologia *Blockchain* para verificação de transações financeiras e alavanca-se contratos inteligentes para gerenciamento seguro de serviços [23].

Também em 2019, [24] apresentam que a mudança no papel do setor de tecnologia da informação dentro das organizações, de um setor responsável por "dominar e dar suporte à tecnologia" para um setor responsável por "melhorar e apoiar continuamente os processos de negócios dos clientes da empresa" possibilitou a redução de problemas como mal-entendidos e insatisfação de funcionários.

Com base nisso, [24] revisam e comparam a literatura sobre práticas de Information Technology Service Management (ITSM) em organizações da administração pública, do setor privado e em bibliotecas, a fim de identificar, dentre outros, até que ponto as práticas de ITSM são diferentes nos setores estudados.

Assim, a partir da revisão da literatura, os autores [24] apresentam algumas características relativas ao ITSM de cada organização. No comércio (setor privado), as propriedades subjacentes ou estrutura dos componentes digitais utilizadas são Client-server model e *Cloud Computing*, e os fatores que influenciam a implementação das diretrizes de ITSM dentro desse tipo de organização são: funcionários (motivação), estratégia corporativa (treinamento da equipe, conhecimento específico do departamento, etc.), os processos, clientes, organização e sua cultura (objetivo da organização, mentalidade e cultura de funcionários individuais) e meio ambiente e infraestrutura.

No setor público, as propriedades de estrutura utilizadas são Client-server model e Databases/servers, e os fatores que influenciam o ITSM são: o ambiente regulatório (leis e regulamentos), a dinâmica do portfólio de serviços (governo eletrônico, por exemplo), o controlador, a orientação ao serviço (por exemplo, entendimento do cliente), a proteção e segurança de dados e o desenvolvimento de pessoal (por exemplo, negociação coletiva e lei da função pública). No caso das bibliotecas, por sua vez, as propriedades de estrutura utilizadas consistem em electronic media, books, CD, etc. e databases/servers, e os fatores de influência são, por exemplo, leis e regulamentos, usuários (estudantes, professores etc), a dinâmica do portfólio de desempenho (por

exemplo, governo eletrônico), os funcionários, a proteção e segurança de dados e o licenciamento [24].

Em 2019 também, [25] apresentam um estudo com o objetivo de avaliar aplicações de Smart Cities sob a ótica da incorporação do *Big Data* na gestão de serviços e na tomada de decisões. Os autores apresentam o *Big Data* como uma resposta aos governos, afim de que estes consigam entender, classificar e utilizar grandes conjuntos de informações gerados pela digitalização da vida social.

A aplicação do conceito de *Smart City*, ou seja, estabelecer uma Cidade Digital Estratégica, carrega consigo o problema do aumento exponencial de dados. Esses dados, consequentemente são o cerne dos serviços prestados por todos. Assim, as informações são essenciais nas Smart Cities para gerir os recursos de uma cidade. E é nesta perspectiva que os autores apresentam a tecnologia *Big Data*, como uma ferramenta para manipular esse volume e variedade de dados no menor tempo possível [25].

Com todo o exposto e considerando que os artigos foram analisados com vistas a identificar questões como qual a tecnologia utilizada/estudada e qual problema ela pretende solucionar, a Quadro 02 apresenta as principais informações encontradas.

Quadro 02: Tecnologias e características de aplicação

TECNOLOGIA	**CONTEXTO**	**PROBLEMA A SER SOLUCIONADO**	**TIPO DE SERVIÇO**	**AUTOR**
Sistema de Informação	Serviços de enfermagem	Disponibilidade de informações confiáveis, válidas e qualitativas.	Atividade interna	[18]
Sistema de gerenciamento de serviços	Governo eletrônico	Burocracia, procedimentos ambíguos, desintegração funcional, estruturas de autoridades vagas e/ou sobrepostas, fragmentação de informações, padronização das tecnologias envolvidas, interoperabilidade entre diferentes administrações públicas, e a introdução de soluções econômicas	Atividade principal	[19]
Web 2.0 e Service-Oriented Architectures (SOAs)	Serviços intensivos em informação	Alta variabilidade, quantificação difícil e terminologia informal	-	[20]
Internet of Things (IoT) e dispositivos terminais portáteis	Turismo	Pontos cegos no canal de serviço, conteúdo de serviço unilateral simples e prestação de serviços passiva	Atividade principal	[21]
Tecnologia da informação (TI) e análise avançada de dados – *analytics*	Hospital	Transparência, eficiência dos serviços e tomada de decisão	Atividade interna	[22]

Blockchain e smart contracts	Banco digital em regiões rurais remotas	Serviços confiáveis sobre redes não confiáveis em regiões remotas	Atividade principal	[23]
Client-server model e *Cloud Computing*	Comércio	Não especificado	-	[24]
Client-server model e Databases/server	Setor público	Necessidade da manutenção de registros e eficiência econômica	Atividade interna	[24]
Electronic media, books, CD, etc. e *databases/servers*	Bibliotecas	Garantir bom atendimento ao cliente	Atividade principal	[24]
Big Data	Setor público	Aumento exponencial de dados no estabelecimento de *Smart City* (Cidade Digital Estratégica)	Atividade principal	[25]

Fonte: Elaborado pelos autores (2020).

Em análise ao Quadro 02, é possível inferir que o setor da saúde, por meio de hospitais e serviços de enfermagem e o setor público, por meio de portais de governo e estabelecimento de estratégias digitais receberam considerável atenção no que se refere à aplicação de tecnologias digitais para solução de problemas. E embora não se tenha encontrado citações das técnologias em duplicidade nos artigos, pode-se verificar tendências de questões nas operações de serviços que carecem de apoio e que podem ser aprimoradas por meio das tecnologias digitais, em especial as tecnologias que tem gerado a chamada Indústria 4.0, como *Blockchain* e *Internet of Things*.

Uma dessas tendências é a aplicação das tecnologias em serviços que possuem pouca informação, e que a falta dessa informação pode gerar ineficiência no serviço e, no caso do setor privado, perda de competitividade e redução de lucros, a exemplo da aplicação de IoT no serviço de turismo. Outra verificação que pode ser feita é o uso de tecnologias onde o excesso de informação traz dificuldades para as organizações, o que vai desde a perda de informações à dificuldade no processo de tomada de decisão. Esse excesso de informações é identificado por meio da aplicação de tecnologias de armazenamento como servidores e repositórios, assim como *Cloud Computing* e tecnologias de manipulação de dados, como o *Big Data*.

Também pode-se inferir que o uso da tecnologia *Blockchain*, tal como sua primeira aplicação, a qual foi realizada para na criptomoeda Bitcoin, também foi estudada para ser aplicada em serviços financeiros, embora possa ser aplicada a qualquer transação de ativos digitais realizada online, tendo o potencial de se tornar uma fonte significativa de inovações disruptivas na área de negócios e gestão [26, 27].

6 Considerações finais

Este estudo teve como objetivo mapear as tecnologias, em especial as relacionadas à transformação digital e por consequência à Indústria 4.0, que têm sido implementadas nas operações de serviços. Como objetivo complementar, buscou-se identificar, além de quais as tecnologias utilizadas, questões como: qual problema essa tecnologia pretende solucionar e em que tipo de serviço ela é aplicada. Embora parte das

informações buscadas não tenham sido encontradas nos artigos do portfólio, ainda foi possível identificar em que setor as tecnologias têm sido aplicadas e quais questões elas têm visado solucionar.

Na Indústria 4.0, devido às mudanças tecnológicas, a maneira como a manufatura digital é usada mudou drasticamente. Muitas das tecnologias utilizadas não são novas, mas as formas de integração, melhorias no uso e uso conjunto mudaram o campo da manufatura digital, abrindo novos desafios e oportunidades [28].

Assim, com base em estudos disponíveis na literatura, foi possível relacionar a aplicação de tecnologias digitais que visam solucionar questões que abrangem tanto o excesso de informações, quanto a baixa quantidade de informações. Isso é verificado por meio das tecnologias que são aplicadas, como no caso de repositórios e serviços em nuvem, a exemplo do *Cloud Computing*, utilizados para armazenamento de informações, e do uso de *analytics* para apoio na análise de informações e tomada de decisão, assim como pela aplicação de tecnologias como o IoT, capazes de fornecer novas informações.

Conforme apresentado na Figura 01, pode-se inferir que a aplicação das tecnologias de informação e comunicação no âmbito da prestação de serviços evoluiu da aplicação de sistemas de gerenciamento a tecnologias que têm sido aplicadas com intensidade na chamada Indústria 4.0, como computação em nuvem e *Blockchain*, o que possibilita entender que o campo das operações de serviços pode ser aprimorado utilizando-se as tecnologias atuais, ainda com aplicações predominantes na manufatura. A partir da Quadro 02 algumas questões podem ser identificadas, conforme descrito na seção de Resultados e Discussões, a exemplo das tendências de aplicação das tecnologias, e que os estudos têm sido direcionados com mais frequência aos setores da saúde e público, por meio de práticas de governos.

Considerando o exposto, entende-se que a principal contribuição desta pesquisa reside na demonstração da possibilidade da aplicação de diversas tecnologias, com finalidades individuais diferentes e que têm sido aplicadas com frequência na indústria, que podem ser aplicadas e trazer benefícios para as operações de serviço. Porém, embora a pesquisa tenha apresentado contribuições, considera-se válida a hipótese de realização de outros tipos de estudo, como empírico ou qualitativo em profundidade, a fim de entender as razões pelas quais as tecnologias têm sido adotadas ou não, percepções, dificuldades, dentre outros, assim como obter mais exemplos de uso de tecnologias digitais em serviço, permitindo mapear de forma mais ampla as tecnologias que têm sido aplicadas, e validando as informações aqui apresentadas.

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Explorando lacunas em modelos de maturidade existentes para avaliação da cadeia de suprimentos inteligente – uma revisão literária

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Resumo: Esse estudo tem objetivo de analisar a produção científica sobre modelos de maturidade aplicáveis para a cadeia de suprimentos inteligente – Smart Supply Chain, publicada em artigos internacionais entre 2016 e 2020. Realizou-se uma revisão sistemática da literatura a respeito desse tema, com os artigos sendo pesquisados nas bases de dados: Scopus, Science Direct e Web of Science a partir das descrições: Maturity Model, Smart Supply, Connected Supply, Digital Enterprise, Industry 4.0.. As publicações analisadas descrevem sobre modelos de maturidade para logística 4.0, a necessidade de maturidade do gerenciamento da cadeia de suprimentos, impacto da indústria 4.0 e da transformação digital no compartilhamento de informações e na tomada de decisões em toda a cadeia de suprimentos, estado da arte da literatura existente da cadeia de suprimentos digital em detalhes e por fim estudam e exploram o status das correntes e as questões para conceituar e discutir as características da cadeia de suprimentos inteligente. Assim, a partir desses achados, observou-se uma lacuna para dirigir estudos visando a mensuração do modelo de maturidade a ser concebido, considerando como atributos recomendações de uso de tecnologias emergentes, sob a ótica da cadeia de suprimentos inteligente.

Palavras-chave: Maturity Model, Smart Supply, Connected Supply, Digital Enterprise, Industry 4.0.

1 Introdução

Os autores [12] apontaram em seus estudos, que na medida em que as cadeias de suprimentos tradicionais estão passando por um processo de transformação, em função da inserção de ferramentas tecnológicas para a tomada de decisão, a cadeia de suprimentos inteligente apresenta oportunidades para gerar: (i) redução de custos e (ii) melhorar a eficiência.

(i) A redução de custos é fator primordial para manter a competitividade das empresas, pois apenas a eficiência dos custos de produção não é por si só, um fator de vantagem competitiva [13].

(ii) A melhoria da eficiência pode ser mensurada através de níveis de modelos de maturidade, que é transferir a filosofia da melhoria de processos do nível do processo para o nível da empresa e, além disso, para o nível da cadeia de suprimentos [4].

O conceito de maturidade pode ser explicado, de acordo com [15], como sendo uma forma de organização de evolução de processos, através de patamares, que são estágios de desenvolvimento. Na medida em que há uma evolução no processo, através de padrões de comportamento e de desempenho robustos quanto à forma e seu conteúdo, o modelo de maturidade se torna aplicável para o desenvolvimento e a melhoria contínua dos negócios [17] com o potencial de ser replicável para vários propósitos distintos. Assim, os modelos de maturidade são ferramentas adequadas para: (i) documentar o status quo atual e futuro; (ii) desenvolver uma visão corporativa para a excelência do processo e (iii) fornecer orientação sobre esse caminho de desenvolvimento [1].

Cadeia de suprimentos inteligente (Smart Supply Chain), é uma cadeia instrumentada, interconectada, inteligente [18], [12] e também automatizada, integrada e inovadora [12]. O uso de sensores, etiquetas RFID e medidores com entidades e ativos de negócios, sistemas de TI, produtos e outros objetos que estão todos conectados e; inteligente: tomam decisões ideais em larga escala para aperfeiçoar o desempenho, através de ferramentas de business intelligence, de acordo com [12], [18] e [7].

Outra característica da cadeia de suprimentos inteligente é a forma ágil e sustentável no seu fluxo de comunicação [19], através da absorção de inteligência incorporada, acompanhando a evolução da Indústria 4.0 para a cadeia de suprimentos, com suas ferramentas de digitalização, automatização, transparência, mobilidade, modularização, redes de colaboração e socialização [20].

A autora [19] explica que isso ocorre devido à redução de custos e o avanço tecnológico e de confiabilidade das tecnologias de sensores, por exemplo, o que faz com que cada processo ou atividade possa ser mensurável. Dessa forma, podem-se criar redes de sistemas interconectados não somente em cadeias de fornecimento com outros fornecimentos, mas também com sistemas de transporte, financeiros, redes de distribuição de energia elétrica. Ainda para [19], com essa incorporação, a gestão da cadeia de suprimentos pode progredir de apoiar as decisões de delegação e de previsão para quais decisões devem ser realizadas, de forma inteligente.

Abaixo, apresentamos a figura 1, onde sintetizamos o conceito de cadeia de suprimentos inteligente – smart supply chain, conforme [18], [12], [19] e [20] e o entendimento dos artigos estudados sob esse tema.

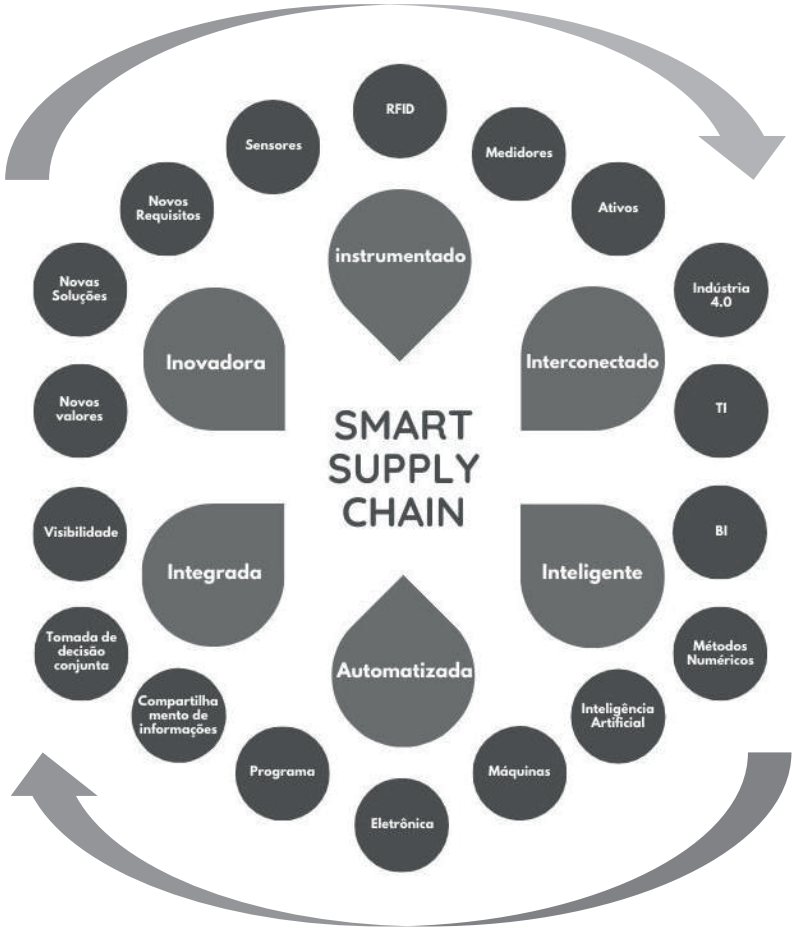

Figura 1 – Conceito de Smart Supply Chain.

Fonte: Autores (2020), adaptado de [18], [12], [19] e [20]

O objetivo deste artigo é fazer uma pesquisa sobre os estudos feitos e os principais tópicos que compõem modelos de maturidade associados à cadeia de suprimentos inteligente publicados nos principais jornais e periódicos acadêmicos no período de 2016 a 2020. Como consequência, uma das contribuições deste trabalho é apresentar tópicos de pesquisa na área que ainda precisam ser explorados e elencar os principais resultados encontrados nas pesquisas desenvolvidas até então.

2 Revisão de Literatura sobre Modelos de Maturidade na Cadeia de Suprimentos Inteligente

Nesse tópico, apresentaremos os trabalhos existentes na literatura nos últimos cinco anos, assim como serão exibidos os modelos de maturidade da literatura. Três pontos serão apresentados: (i): método de estudo; (ii) literatura acadêmica e (iii) principais pontos de contribuição para o tema, explicados conforme afigura da trilha de estudos abaixo:



Figura 2 – Trilha do estudo.

Fonte: [6] adaptado pelos autores (2020).

2.1 Método do estudo

Duas dimensões foram utilizadas para classificar os artigos analisados:

i) Dimensão do período da busca dos últimos cinco anos. As bases de dados consultadas foram: Scopus, Web of Science e Science Direct; utilizando as seguintes palavras chave: Maturity Model, Smart Supply, Connected Supply, Digital Enterprise, Industry 4.0. Essas palavras chave foram combinadas aleatoriamente, para gerar combinações diferentes. O sufixo

de referência utilizado foi o operador AND em todas as combinações. Dessa forma, obtemos a busca com as duas palavras-chave simultâneas na relação de artigos a serem buscados nas bases pesquisadas.

Tabela 1. Relação de artigos localizados nas bases de dados

Base	Keywords	2020	2019	2018	2017	2016	∑
Scopus	Smart Supply AND Industry 4.0	11	71	63	28	17	190
Scopus	Supply 4.0 AND Connected Supply	02	23	14	14	11	64
Scopus	Digital Enterprise AND Smart Supply	0	14	16	8	7	45
Scopus	Maturity Model AND Supply Chain 4.0	0	1	8	2	0	11
Science Direct	Smart Supply AND Industry 4.0	7	23	10	4	2	46
Science Direct	Supply 4.0 AND Connected Supply	2	3	3	4	0	13
Science Direct	Digital Enterprise AND Smart Supply	1	3	4	1	0	9
Science Direct	Maturity Model AND Supply Chain 4.0	0	1	0	0	0	1
Web of Science	Smart Supply AND Industry 4.0	8	61	44	15	13	141
Web of Science	Supply 4.0 AND Connected Supply	3	21	13	9	8	54
Web of Science	Digital Enterprise AND Smart Supply	0	8	5	4	2	19
Web of Science	Maturity Model AND Supply Chain 4.0	0	0	1	0	0	1
	Total de Artigos no Período 2016-2020						594

Fonte: Autores (2020)

ii) Dimensão da metodologia empregada para detecção do nicho da pesquisa: o uso da metodologia CARS – Creating a Resource Space – de [6]. Esse método consiste detectar a pesquisa em três blocos:

(a) **Estabelecimento do território da pesquisa**: Emprego de palavras-chave de acordo com os assuntos sobre cadeia de suprimentos inteligente em suas bases de dados, como já citado anteriormente. Além disso, criamos um espaço de busca entre 2016 a 2020, por ser um tema recente.

(b) **Estabelecimento do nicho da pesquisa**: conforme a **Tabela 1**, 594 artigos foi localizada. Foram criados critérios de inclusão e exclusão para determinar os artigos que seriam selecionados para o estudo. A exclusão de publicações não relevantes de acordo com o JCR – Journal Citation Report < 1 e análise da leitura de 51 resumos dos artigos completos. Após esse processo, foram selecionados artigos, de acordo com a aderência ao tema da pesquisa. Assim, estes artigos que tratavam do tema cadeia de suprimentos inteligente e modelos de maturidade na cadeia de suprimentos, foram estudados 10 artigos na íntegra, mas de forma isolada.

(c) **Ocupando o nicho da pesquisa:** dessa forma, ao associar os estudos de métodos para mensurar o modelo de maturidade, somados aos estudos de cadeia de suprimentos inteligente, ocupamos o nicho da pesquisa, que será apresentado mais adiante.

2.2 Literatura acadêmica sobre o tema

2.2.1 Conceito de Modelos de Maturidade

Os primeiros estudos envolvendo modelos de maturidade ocorreram na área de Engenharia de Software [8] e na área de Qualidade, com o grid de maturidade de Crosby [9]. Os modelos de maturidade servem para avaliar o nível de desenvolvimento das capacidades de uma organização em relação a um domínio [10], através da evolução de patamares, que são estágios de desenvolvimento [15]. Assim, é uma metodologia que possui por objetivo uma linha de crescimento para atingimento da excelência na organização.

Na medida em que há uma evolução no processo, através da avaliação do padrão de desempenho da organização, modelos de maturidade são ferramentas para promover o desenvolvimento e a melhoria continua dos negócios [17], sendo o Capability Maturity Model (CMM) desenvolvido no início dos anos 1990 e que evoluiu para Capability Maturity Model Integration [17], o que foi para os autores [11], um estudo disseminador do uso da ferramenta para várias áreas do conhecimento.

A estrutura do CMMI é baseada em cinco níveis de maturidade e incluem ainda em suas categorias atributos comuns (tipos de atividades) e qualificadores (atividades) [11]. Dessa forma, pela sua natureza genérica de apresentação, várias áreas do conhecimento passaram a utilizar o modelo de maturidade para avaliar a evolução de processos.

Posteriormente, outros modelos foram criados outros modelos de maturidade, como CSC Framework, Business Process Orientation Maturity Model (BPOMM) e Supply Chain Management Maturity Model (SCMMM) [21]. Esses modelos possuem cinco níveis também, que se equivalem aos apresentados na **Tabela 2 –** Níveis de Maturidade.

Tabela 2. Níveis de Maturidade – CMMI

Níveis	Qualificadores
Inicial	Poucos processos são definidos
Gerenciado	Processos básicos são definidos
Definido	Processos documentados e padronizados
Nº Gerenciado	Processos numericamente controlados
Otimização	Processos em melhoria contínua

Fonte: Adaptado de [11]

Tratando de maturidade na cadeia de suprimentos, o conceito de maturidade tem sido aplicado na cadeia de suprimentos como um método de avaliação e um modelo de melhoria contínua no atingimento dos objetivos do negócio [21]. Portanto, da mesma forma que os demais modelos de maturidade apresentam um modo genérico de estrutura, mas a sua estrutura de atributos muda conforme a necessidade de determinar o nível daquilo que está sendo avaliado.

2.2.2 Apresentação dos Modelos de Maturidade da Cadeia de Suprimentos na Literatura

Apresentamos na Tabela 3, uma amostra dos modelos de maturidade estudados. Preliminarmente, interessante observar que 80% da amostra analisada, há presença de cinco níveis de maturidade, assim como os atributos possuem sua proposta de forma semelhante, que denominamos como genéricos sobre os modelos.

Tabela 3. Amostra dos artigos que tratam sobre modelos de maturidade, conforme os critérios de busca desse estudo

Autor / Ano	Níveis	Atributos Genéricos
[2]	7	1 - agregação de valor; 2 – encanto; 3 – relações com fornecedores; 4: envolvimento; 5 – gerenciar custos; 6 – melhoria contínua e 7 – desenvolver pessoas
[5] [22] [21] [1] [12] [11]	5	1 – inicial; 2 – padronização; 3 – definindo; 4 – gerenciado; 5 – melhoria contínua.
[23] [24]	3	1 – custos e estrutura; 2 - gestão dados e tática; 3 – alta liderança e analytics

Fonte: Autores (2020)

Para [2], os sete princípios descritos apresentam processos fundamentais para a implantação eficiente de uma gestão da cadeia de suprimentos. A estes sete princípios, o autor denominou de níveis, no qual a partir de cada nível superado, a organização tende a obter um funcionamento equilibrado ou "maduro" como próprio autor citou dentro de uma cadeia de suprimentos interdependente. Assim, [2] apresenta os níveis e atributos: primeiro nível: competir através de valores superiores em termos de lucro e de volume de negócios, visando atividades de agregação de valor financeiro e combate a desperdício, passando por estreitar relações com fornecedores, gerenciar os custos e os riscos associados e desenvolver a melhoria contínua, para que por fim, em seu último dos sete níveis apresentados, o autor cita em desenvolver, treinar pessoas dentro da cadeia de suprimentos.

Para o nível de maior incidência da pesquisa, os cinco níveis de maturidade foram definidos na etapa inicial como um entendimento do status quo atual em relação as práticas realizadas internamente na organização para obter um mapeamento da

integração entre as áreas da cadeia de suprimentos e de seus clientes, para posteriormente desenvolver um plano escalonado para aumentar suas competências internas para reposicionamento do fluxo de comunicação e de relacionamento entre as áreas envolvidas, conforme [21], [1], [12] e [11]. Na medida que apresenta uma evolução palitativa para as demais etapas, visa a padronização de rotinas e de processos de comunicação e de estreitamento de relações já num patamar intermediário de maturidade [22] de forma a controlar a flexibilidade entre empresas junto com seus sistemas de TI, de forma a permitir a troca de informações e eventualmente o replanejamento conjunto entre clientes e fornecedores, integrando com dados internos (por exemplo, capacidades, pedidos, vendas, previsões) [22]. Uma vez essas práticas e processos definidos, são sistematicamente gerenciados através da continuidade de otimização dos processos de modo a garantir a melhoria contínua [5] da cadeia de suprimentos.

Importante salientar, conforme [12], que a cadeia de suprimentos inteligente como o novo sistema de negócios interconectado que se estende desde aplicações isoladas, locais e únicas empresas até implementações inteligentes sistemáticas de toda a cadeia de suprimentos. Para [12] ainda comentam que a cadeia de suprimentos inteligente deve possui a maioria dos recursos discutidos acima, incluindo a suas respectivas tecnologias como IoT, máquinas e infraestrutura inteligente, e recursos como interconectividade, permitindo totalmente a coleta de dados e a comunicação em tempo real em todas as etapas da cadeia de suprimentos, tomada de decisão inteligente e processos eficientes e responsivos para melhor atender os clientes. Dessa forma, as atividades apresentadas aqui até então, de acordo com o escopo do estudo, deverão ser compreendidas na forma "o que fazer" para determinar os níveis de maturidade, no entanto, "o como fazer" as atividades, ou seja a operacionalização delas, remetem aos sistemas provenientes do smart supply chain.

Os autores [23] e [24] citam três níveis de maturidade – inicial, intermediário e final, remetendo-os aos mesmos pontos dos modelos de cinco níveis, onde há um agrupamento de níveis intermediários (dois, três e quatro) numa única etapa, porém há uma alteração de foco em gestão de dados e do maior envolvimento do nível tático e operacional nos processos, onde o nível de melhoria contínua, mais comumente apresentados nos outros modelos de maturidade, entra em evidência a visão de analytics [24]. Assim, compreendemos que essa proposta de modelo é voltada para a apresentação níveis de maturidade analíticos diversos, como o Business Intelligence Maturity Model (BIMM) [25]. A natureza genérica de apresentação dos modelos de maturidade pode permitir que outras áreas do conhecimento usar o modelo de maturidade para evolução de processos. Como trata de smart supply chain a pesquisa, esse modelo também pode ser utilizado no processo na etapa inteligente do conceito cadeia de suprimentos inteligente.

2.2.3 Principais pontos de contribuição da literatura acadêmica sobre o tema

A análise dos modelos de maturidade estudados na literatura foi realizada de acordo com os itens que conceituam a cadeia de suprimentos inteligente, como um

sistema de negócios interconectado [12]. É uma cadeia instrumentada, interconectada, inteligente [18] e também automatizada, integrada e inovadora [18] e [12]. Assim, na análise desses itens, procurou-se estabelecer uma relação de nexo causal entre o conceito de smart supply chain e os elementos necessários para a concepção de um modelo de maturidade, analisando não somente os artigos que tratam sobre cadeia de suprimentos inteligente, mas também artigos que permeiam o tema, com assuntos periféricos sobre smart supply chain, através do entendimento dos conceitos de supply chain management e de que forma esses conceitos abordados poderiam de alguma forma enriquecer o estudo com constructos teóricos.

Através desse entendimento, concebemos o Quadro 1, com o intuito de apresentar uma relação de artigos selecionados na literatura que contribuem para os estudos de modelos de maturidade de smart supply chain, conforme os critérios estabelecidos e explicados acima. Esse quadro foi dividido através dos seguintes itens: (i) extração autor e título; (ii) interpretação do artigo e; (iii) relação de achados quanto estrutura de atributos e níveis.

Quanto ao item estrutura de atributos e níveis, segue os princípios apresentados por [16], através de suas definições sobre Business Process Orientation – BPO, pois esses autores apresentam em seus trabalhos que a BPO é fundamental para gerar subsídios para obter maior conexão dentro de uma organização, enquanto melhora a performance dos negócios. BPO para [16] apresenta princpalmente os seguintes elementos-chave: gerenciamento, medição, e aspectos do processo. Assim, a compreensão da estrutura de atributos e níveis são aspectos importantes, não apenas para a concepção do modelo de maturidade, mas para serem direcionadores para o processo de evolução da melhoria contínua nesse ambiente de smart supply chain.

Quadro 1. Relação de artigos selecionados que contribuem para os estudos de modelos de maturidade de smart supply chain

Contribuição	Detalhe dos níveis e atributos
Esta pesquisa enfoca o impacto do "Industry 4.0" e "Digital Transformation" no compartilhamento de informações e na tomada de decisões em toda a cadeia de suprimentos. Seguindo uma abordagem qualitativa demonstram que uma avaliação e integração da cadeia de suprimentos baseada em novas tecnologias ainda estão distantes.	Avaliação da cadeia de suprimentos digital (sinônimo de inteligente) através dos 5 atributos listados: 1) Hardware, 2) Software, 3) Pessoas, 4) Processos e 5) Dados; nessa ordem.
Apresenta metodologias de gerenciamento da cadeia de suprimentos que, baseadas nos princípios do pensamento enxuto integrados aos conceitos da indústria 4.0. e uma política de compartilhamento de dados em tempo real.	5 níveis: 1) Identificação 2) Planejamento de alternativas; 3) Implementação das propostas; 4) Avaliação da implementação e, 5) especificação do aprendizado.

Este estudo propõe uma nova estrutura para identificar o SCMP (Supply Chain Management Practices) inteligente-sustentável como critério de seleção de fornecedores para uma cadeia de fornecimento inteligente para uma seleção sustentável de fornecedores para uma cadeia de fornecimento inteligente..	4 atributos identificados na leitura foram: Redução de custos usando tecnologias inteligentes (EC1); Melhoria da qualidade do produto (EC2); Entrega inteligente ao cliente (EC3) e Melhoria da flexibilidade de fornecimento (EC4).
Este artigo tem como objetivo conectar cada uma das principais tecnologias qualificadoras da I 4.0 com os paradigmas mais significativos da cadeia de suprimentos: Lean, Agile, Resilience	5 níveis 1) Econômicos, 2) Energéticos e 3) Ambientais através da implementação das seguintes qualificadores – tecnologias: Robôs Autônomos, Fabricação de Aditivos, Computação em Nuvem, Robôs Autônomos, Cyberse- curity e Realidade Aumentada. Uma segunda fase onde convergem os atributos 4) Funcionais e 5) Sociais através da implementação das seguintes qualificadores – tecnologias de Integração Horizontal e Vertical, Grandes Dados, Blockchain, Simulação, Internet das Coisas e Inteligência Artificial,.
Assim, as principais contribuições do estudo são (1) o desenho de artefatos prescritivos que descrevem as relações no SSCM, (2) oferecer funcionalidades direcionadas e avaliadas de apoio à decisão para cadeias de abastecimento sustentáveis, e (3) fornecer um terreno fértil para futuras pesquisas.	5 níveis que os autores apresentam com enfoque em sustentabilidade da cadeia de suprimentos, 1) não é ciente e não cumpre nada sustetnável; 2) medidas ainda tímidas e desconectadas com a alta direção; 3) As metas/normas de sustentabilidade definidas e seus KPIs.; 4) de conformidade para sistema de medição de desempenho; 5) **C**onceito totalmente integrado com propagação de conceitos estratégicos e Melhoria Contínua.
Modelo de maturidade para logística 4.0. Além disso, os resultados mostram que o amplamente utilizado modelo de referência de operações da cadeia de suprimentos pode servir como base para modelos adicionais de maturidade do processo.	São 5 níveis de maturidade com os seguintes atributos: 1) digitalização básica: muitos processos manuais 2) digitalização entre áreas departamentais; 3) digitalização horizontal e vertical: integração em toda a empresa no sistema operacional IoT baseado em nuvem; 4)

	digitalização completa em tempo real IoT e 5) digitalização total otimizada IoT
O modelo de maturidade de cadeia de suprimentos apresenta um estrutura de melhoria aplicável para a implementação bem-sucedida da gestão da cadeia de suprimentos.	7 níveis: Princípio 1: valor lucro/volume de negócios Princípio 2: definir os valores do cliente Princípio 3: estabelecer relações com fornecedores. Princípio 4: integrar as atividades do projeto. Princípio 5: gerenciar os custos de forma colaborativa. Gerenciamento de risco Princípio 6: desenvolver a melhoria contínua Princípio 7: mobilizar e desenvolver as pessoas
Demonstra a necessidade de maturidade do gerenciamento da cadeia de suprimentos na implementação das melhores práticas	Os autores definiram três níveis de maturidade, primeiro inicial onde não há práticas definidas, o segundo e o terceiro, mostrando que Fornecedores e inventário, Recursos Humanos, Estratégia e planejamento, Processos e Tecnologia da Informação estão no segundo nível de maturidade, enquanto que Liderança e cultura, Desempenho e Clientes estão no terceiro nível.

Fonte: Autores (2020)

3 Resultados e análises – níveis e atributos

Os autores [14] apontaram em seus estudos, uma classificação de atributos de modelos de maturidade, que são usados para conceber uma visão geral do modelo. Ainda segundo esse autor, os atributos são divididos em três categorias: gerais, design e uso do modelo. Vamos adotar essa estrutura para apresentar os principais achados dos níveis e atributos dos modelos de maturidade analisados até então.

Durante os estudos, observamos a importância de possuir uma métrica para mensurar não apenas de maturidade, mas sim o seu grau de evolução, pois também desenvolveremos ao longo do estudo, indicadores para cada um dos atributos, de forma a obter subsídios para avaliar o grau de evolução de cada nível, conforme [21].

Esse conceito aqui apresentado é crucial para a pesquisa, pois no decorrer dos estudos, em planos futuros na etapa decisional e prognóstica sobre a recomendação do uso de tecnologias 4.0 no ambiente smart, serão as bases para a formulação de critérios visando à concepção do modelo de maturidade, utilizando como base a estrutura apresentada nos estudos de [14], apresentando a sua estrutura de atributos, de acordo com a leitura dos artigos citados no tópico anterior.

Os autores [3] em seus estudos mostraram que a Indústria 4.0 e a Transformação Digital têm o potencial de alcançar uma integração total do SC digital em termos de maior transparência, por exemplo, através de plataformas centralizadas. Para esses autores, um problema central da digitalização dos processos em todo o SC em termos de troca de informações entre parceiros comerciais é a falta de padrões para o processo de compartilhamento de informações de um ponto de vista tecnológico. Nos seus estudos, ele apresenta 5 níveis de avaliação da cadeia de fornecimento. Esses 5 níveis podem ser interpretados também, como níveis de maturidade para a transformação digital, pois de acordo com [14], a maturidade implica um progresso evolutivo na demonstração de uma habilidade específica ou na realização de um alvo desde uma inicial até um desejado ou normalmente ocorrendo no estágio final.

Através desse conceito, extraímos esses pontos de avaliação dos estudos de [3] para serem itens de aprofundamento de estudos para propor um método de avaliação para em nível de avaliação da cadeia de suprimentos inteligente. Para isso, os atributos desse modelo permeiam os pontos: Hardware, Software (visando a padronização no compartilhamento de informações), com Pessoas, Processos e Dados.

Os autores [1] apontaram em seus estudos, uma estrutura de níveis e atributos relacionados as ferramentas de transformação digital para tornar um processo de supply chain management inteligente, o processo fim da cadeia, a etapa de entrega. Nessa proposta, os autores propõem um modelo genérico de maturidade com 5 níveis:

(i) Digitalização básica; (ii) Digitalização entre os departamentos; (iii) Digitalização horizontal e vertical; (iv) Digitalização completa e (v) Digitalização completa otimizada.

Os seus atributos de cada um dos níveis apresentados são (i): fluxos de informações são recebidos de forma manual. Não são sistemas que os concebem. O input é feito no sistema a partir de uma informação manual.

No atributo seguinte (ii): recebe-se de forma eletrônica dados de consultas de clientes e solicitação de cotações via interface padronizada e com resposta eletrônica às consultas do cliente e solicitação de cotações via interface padronizada.

O atributo (iii) apresenta o recebimento automático de consultas de clientes e solicitação de cotações através de interface padronizada e acesso às informações de processamento de pedidos através de dispositivos móveis.

Os atributos seguintes (iv) já deixam de ser um padrão intermediário de maturidade e migram para uma dimensão avançada, pois ocorre a digitalização completa em ambiente IoT, com recebimento automatizado em tempo real de consultas e solicitações de orçamentos por parte dos clientes, recurso a dados específicos do cliente, e resposta automatizada em tempo real a consultas e solicitações de cotações de clientes.

A etapa (v) digitalização completa otimizada conta com recursos de simulação em tempo real para tomada de decisão; análise automatizada de consultas de clientes, solicitação de cotações ou transmissão de dados em caso de falha; e habilidades de autoaprendizagem a partir de casos de falha resolvidos – entrando na questão da inteligência artificial.

4 Conclusões

Os autores [1] apontaram em seus estudos, uma lacuna para continuidade de pesquisas para a cadeia de suprimentos inteligente, pois esse estudo focou em apenas o processo de entrega. E esse gap foi detectado na revisão literária sistemática, assim, vamos dar continuidade nos estudos desse modelo, extrapolando além do processo de entregar propôs em seus trabalhos, mas para fazer uma análise da cadeia de suprimentos como um todo, focado no conceito smart supply chain.

Para [12], desenvolver o sistema de informações para uma cadeia de suprimentos inteligente, provavelmente deve-se começar com perguntas sobre quais informações a empresa e outros parceiros da cadeia de suprimentos precisam e responder perguntas sobre quais informações eles podem fornecer para beneficiar a si mesmos e a outros parceiros. Dessa forma entendemos que o ponto chave para criação dos níveis e atributos para avaliar a cadeia de suprimentos inteligente é, conforme [14], uma descrição de cada elemento ou atividade e como ela pode ser realizada em cada nível de maturidade.

Assim, um dos achados importantes dessa pesquisa foi compreender que os níveis de maturidade apresentados de forma genérica quanto a sua classificação, mas ao conceber os atributos que qualificam a evolução do modelo proposto deverão permear as inovações e as ferramentas da indústria 4.0 para avaliar a cadeia de suprimentos inteligente, de acordo com sua definição smart.

A partir desse resultado, vamos dar continuidade na pesquisa focando métodos de avaliação do grau de maturidade em outras áreas de estudo, e verificar a possibilidade de incorporar métodos de diferentes áreas do conhecimento para a replicação de outros métodos de avaliação do nível de maturidade da cadeia de suprimentos inteligente.

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Service Network Design Problem in freight transportation. A literature review

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Abstract. Logistics service providers have to offer their clients highly reliable and high-quality services at competitive prices while ensuring constant technological updates in equipment, and looking after their profits. To face this challenge, transportation service companies have chosen to consolidate goods that share a vehicle to be delivered. However, the design of these services involves taking decisions about the frequency, the type of vehicle, and the route of the service. This problem is typified in the literature as a Service Network Design Problem, which may include stochastic elements in the formulation of the problem, the objective of which is to determine the vehicle departure schedule, and the delivery sequence merchandise for companies dedicated to offering cargo transportation services in Mexico. In this review, it is showed a state-of-the-art review of the Service Network Design Problem and its current challenges.

Keywords: Service networks, LTL service, freight transportation, transportation optimization, service network design problem.

1 Introduction

Freight transportation is a highly competitive sector, where carriers have to offer reliable, high-quality services at competitive costs, given a set of potential resources and a demand to satisfy. A freight transportation plan must be designed that meets both parameters to guarantee customer satisfaction considering minimizing the total costs incurred when providing a service. To achieve the balance of customer-supplier profits, the Design of Service Networks problem has been formulated, which include strategic decisions such as the size and allocation of the fleet, the acquisition or subcontracting of third parties, the tactical decisions that define a plan, and a repeatable transportation schedule. Early research indicated that in realistic instances of such planning-level

problems were hard to solve. However, with progress in scientific research, some of these practical problems have been modeled and solved using more sophisticated mathematical programming techniques.

The less-than-truckload (LTL) trucking industry uses consolidation as a means to increase service frequencies while keeping costs under control. This is performed by transporting various products, established for different destinations, from one terminal to a distribution center. There they are consolidated with other products that come from other terminals before being sent out of the center. Products can be loaded and unloaded at various hubs/breakbulk before reaching their final destinations. This use of consolidation provides a lower cost compared to not consolidating the freight [1].

Typically, Service Network Design is a part of planning activities, although it is often referred to as strategic/tactical or tactical/operational following planning traditions and company horizons. The objective is to operate efficiently to respond to demand and guarantee the profitability of the company. The supply side of this equation involves a view of network operations throughout the system, integrating consolidation activities at terminals, and selection, routing, and scheduling of services. On the demand side, the route of the cargo through the network must be planned to ensure timely and reliable delivery to meet customer's specifications and the carrier's objectives [2].

2 Problem Statement

Network flow planning relates to flow planning decisions that address the movement of orders (commodities) throughout the network. The input parameters include a hub-and-spoke network, where the merchandise will be consolidated, with a set of nodes N and a set of arcs A

In addition, values are given for fixed and variable network costs. Fixed costs cover costs $c_{a\ ,ij}$ or services in a single network arc. The variable costs $c_{c\ ,ij}$ represent the costs of each unit of merchandise flow between the pairs of nodes $_{,ij}\in$ N. As demand parameters, a transport demand d_{ij} s given for each pair of nodes $_{,ij}\in$ N, which must be satisfied by the network. In [3] the author defines a difference between dynamic and non-dynamic service network design problems, so the latter incorporates the dimension of time in the model. In this case, the transportation times t_{ij} between the pairs of nodes $i, j \in$ N as well as the transshipment times t_h for each central node h is added [4].

Continuing the classification elaborated by [3], we highlight the introduction of decision variables in service networks, and these networks respond to dynamic or non-dynamic services either with a given network structure or a variable network structure. The attributes of these dimensions are listed below.

I. Dynamic service network with variable network structure. The capacity of the service is calculated through the frequency or by the number of services

within a certain schedule, or also, by defining the number of services in the network within a certain planning period.

II. Dynamic service network with a given network structure. In this network, transportation schedules are provided, and services are chosen from a pre-defined set of orders.

III. Non-dynamic service network with variable network structure. In this type of network, it is determined a subset of open arcs without considering transportation schedules.

IV. Non-dynamic service network with a given network structure. Similar to a network flow problem.

In Fig. 2 it is presented a classification of the problem.

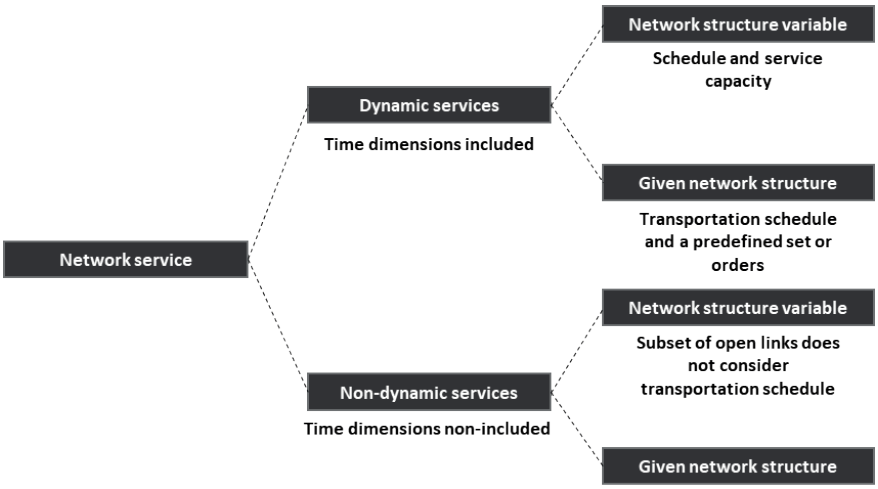

Fig. 1. Service Network Design Problem classification, based on [3].

The variable transportation costs within a network are closely related to the flow of freight so that a change in the choice of transport service offered can reduce the costs of the flow of goods or the overall costs of the operation can be reduced by balancing fixed and variable costs. However, the design of a service network not only seeks to reduce them, depending on the focus of the company, the maximization of benefits is also sought. In this sense, the benefits will be given by the willingness that the client has for paying high prices for the services offered even if, for the company, it does not contribute to efficiency.

3 Methodology

The development of this research was carried out through the implementation of the hypothetical deductive method where, from the statement of a hypothesis, the search for information that would support said approach began. In the Network Service Design

Problem, the optimization of the vehicle travel times could be achieved by building a network of services to consolidate freights and establishing vehicle departure times based on quantitative methods.

Based on this premise, a work plan was determined to carry out the study that includes three stages as follows. The first stage consisted of a preliminary review of the literature, without being exhaustive regarding the Design of Service Networks to have a general concept. In the second stage, the research guideline was established, setting key concepts that delimited the research. Due to the magnitude of information for Network Design and according to the main focus of the study, the search was limited to concepts such as "Freight Transportation", "Consolidation", "LTL", and "Design of Stochastic Service Networks". Under this approach, the search was conducted in Science Direct databases. With this information, in the third stage, a referential framework was built regarding our initial premise; there were identified retrospective articles that contain the key concepts and various variations in the formulation of the Service Network Design. Finally, it was made a comparison between the performance measures, parameters, and approaches of the models used.

4 Literature review results

The objective of the design of a freight service network is to determine how the freight transportation service has to be performed, to satisfy the current demand and meet the economic objectives of the transportations companies and their customers' level of service through the approach of mathematical models and the algorithmic approach needed. However, the scope of the mathematical models formulated and their corresponding algorithms had been somewhat limited because of the computational complexity involved. [2] and [3] show the formulation of the Service Network Design Problem for long-distance land transportation. The results are impressive concerning the impact of the system both in the context of cargo planning operations and for strategic studies of possible terminal locations.

The specialization in the design of service networks, now dynamic (SNDPD), is presented by [5] who make a formulation with stochastic values that depend on time, aims to optimize the problem in a given planning horizon and propose a solution approach based on dynamic programming principles from a single terminal that dispatches services to several Clients and other terminals, coupled with this model, propose a static, single-period formulation of the single node problem that appears as a subproblem when addressing the time-dependent version and general service network design cases.

In [1] the authors introduce the correlations between the random demands in a service network design problem affect the optimal routes of trucks, as well as the flexibility in the shipment of basic products. demonstrate that a design can be flawed if it is based on incorrect correlations. The consolidation of merchandise that takes the role of

shipping small loads together over long distances and in turn coverage is also considered for the approach of this model; When random demands travel the same paths, particularly if they are negatively correlated, consolidation implies hedging. The solution is carried out through simulation techniques that included generation of scenarios, and indicating that if a procedure for such generation produced random or biased correlations.

With an application in a transportation network in Europe, in [6] different formulations of problems published in the literature were evaluated. It was conducted analyzes and comparisons of the specific solution, showing that good solution approaches have been developed for the SNDPs. Generally, all problems are focused on a particular part of the entire tactical planning problem. On the other hand, [7] presents a model attached to the needs of the design of a service network for a company providing a viable weekly-use planning tool. This situation enables LTL companies to regenerate load plans every week based on the most up-to-date and accurate load forecast with the latest load trends.

Uncertainty in the demand of services or products plays an important role in the construction of schedules in the design of service networks, solutions based on uncertain demand have characteristics that provide value in terms of operational flexibility with robust schedules. Structural differences prevail that differ from deterministic solutions. Among the main differences is in the number of routes between the origin and destinations, as well as the use of vehicles resulting from the consolidation of goods, which represents the main correlation problem, the correlation between merchandise and it is here where the work carried out in [1] and in [8] makes contributions to the primary model.

Once stochastic elements and time dependence are considered in the design of the service network, in [9] it was represented fluctuating demand through scenarios and integrating a model that has a balance of empty vehicles, cost of loading in intermediate terminals, costs associated with the movement of cargo using the selected services and the penalty costs for not being able to deliver the load. That is, it is the first approach to real network design problems with a metaheuristic algorithm and is closely related to the work of [1]. Another metaheuristic algorithmic contribution was introduced by [10] through a hybrid Taboo Search model, which reduced the calculation time by more than a third.

In [11] continues with an extension of a stochastic programming model from [8] and proposed a network design model with vehicles re-routing, as well as the outsourcing of services to handle the uncertainty of demand. A set of integer variables for modeling the detour of vehicles is introduced in the second stage of the stochastic program. The results offer various redirection options and flexibility to handle uncertainty. Although the model seems to adapt to a real case, the contribution is focused on study cases taken from the literature.

In [12], the authors developed an algorithm to solve service network design problems that use expanded networks in time, which avoids having to introduce model approximations, which improves the quality of the solution, to maintain the size of the expanded time. The results through Solve-CTSNDP is quite effective. However, there are improvements that will increase its efficiency. One of them is in the initial iterations, which suggest solving through the relaxation of linear programming or solving the problem within a proven percentage of optimization.

In [13] highlights the impact on the quality of the solution to the approach to the design of service networks where networks expanded in time are common to model transport problems, however, their use requires that a discretization scheme is chosen. Empirical results show that this is an important choice since the main loss in solution quality is due to the loss of viable low-cost routes over time and the loss of potential consolidations. Instances with high flexibility are less affected by coarse discretization but can be hard to solve, with high-cost rates, as high flexibility allows greater consolidation possibilities, and a high-cost rate emphasizes consolidations over routes.

The contributions of [14] are brought together for them by developing a scheduled service network design model that addresses strategic decisions regarding fleet size and allocation, including procurement and subcontracting, as well as tactical decisions regarding scheduled repeatable transportation plans. Given the computational difficulties associated with the exact resolution of stochastic programs, they propose two ways based on the generation of columns to approach the model. They proposed a heuristic model based on the column generation technique, which decomposes the optimization problem into multiple dimensions and evaluates a neighboring solution in all scenarios; also by applying the knowledge in two instances of an LTL carrier. The second is based on the network of a European postal carrier. The results of the effectiveness of the proposed heuristic methods suggest a study of the impact of the operating environment on managerial decision-making, both at the strategic and tactical levels.

The problem of routing and design of service networks that integrates local and long-distance transport planning decisions is important for consolidated service carriers that need to provide efficient services that involve the synchronization of their movements. [15] present two formulations to this problem, the first is based on a set of rules for local deliveries which has greater ease of modeling compared to the second approach with faster time resolution but more limited modeling.

[16] propose deterministic robust optimization formulations and two-stage use a set of uncertainties without probability to face the uncertainty of the demand in the proposed robust model. Where the Bender decomposition method is lessened in contrast to the column generation approach and restrictions used. They also analyze the impact of considering multiple types of services in the transportation system, confirming that diversifying the types of services helps to reduce the total cost and the optimal total number of vehicles used in the network. The quality of deterministic solutions in sto-

chastic service networks is studied by analyzing time-dependent formulations (scheduled services), they propose a measurement scheme to evaluate the level of potentially beneficial structural properties (use of multiple routes and route sharing) in different solutions. The results show that the structural properties have high impact and are correlated with the performance of a solution in the stochastic environment [17]. In [18] the authors work on the stochastic problem of programmed service network design, but now it includes the uncertainty in travel times, as well as the quality of deliveries referred to the punctual operation, the solution of this approach is generated through of a metaheuristic based on progressive coverage. Finally, [4] summarize the current state of the different modes of transport as of 2008 and categorize in terms of problem characteristics, model formulations and solution approaches, including uncertain demand, transport times, costs and capacities, this was our reference in the realization of this work.

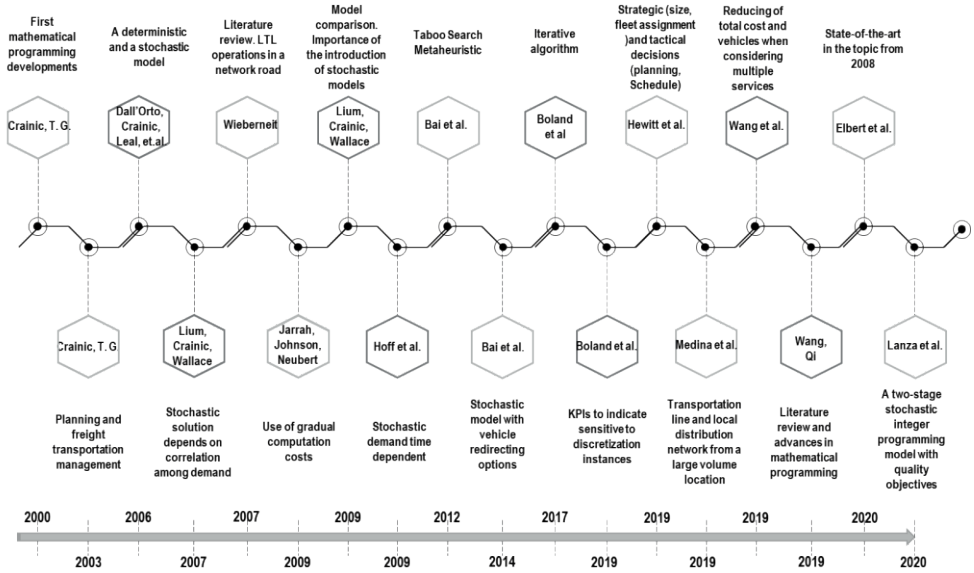

Fig. 2. Timeline of the main findings in the Service Network Design Problem.

5 Conclusions

The present state-of-the-art allows correctly dimensioning the importance of the Service Network Design Problem topic. It is possible to recognize that the incorporation of stochastic considerations is necessary, especially in those related to the demand side. From the perspective of those who offer the transport service between links in the supply chain, the ultimate goal would be to achieve a scheme that helps to determine pre-positioning strategies of the vehicle fleet in strategic locations. Hence, it is expected to use the elements listed in this review to define the state variables, the performance measures, and the elements that allow modeling for a customized study case.

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Exploring Interconnections between Machine Learning and Operations Strategy

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Abstract. Within the data science and artificial intelligence fields of study, machine learning have supported performance improvement in medicine, manufacturing, law and even sport environments. The purpose of this paper is to investigate how machine learning has been used as a tool to improve the assertiveness of decision- making, providing competitive advantages in the wide field of operations management. This exploratory research analyzes the content of five machine-learning studies, relating each of them to Slack's strategy pillars: cost, speed, quality, flexibility and dependability. Research design was limited to Scopus' papers published exclusively in high impact journals. Results emphasize the important role of machine learning in organizational competitive advantages and limitations are used to address further research suggestions, extending the present investigation with a more extensive bibliographic portfolio analysis. The contribution of this paper is a matrix analysis of how machine-learning projects indirectly contribute to at least three strategy dimensions simultaneously. Complementarily, an illustration was built for a better comprehension of the interrelationships among the strategic pillars reinforced by the analyzed studies.

Keywords: Slack, machine learning, operations strategy, strategy, operations.

1 Introduction

Strategy has a variety of different concepts, with multiple perspectives and definitions, which are considered important for academic research, since this diversity can offer distinct horizons and guidelines (Mintzberg, 1987, Skinner, 1969). Porter (1996) reinforced this point of view and tried to differ strategy from operational effective-

ness, since its importance is not enough to achieve competitive advantages. With Industry 4.0 and artificial intelligence scenario, organizational environment became even more aggressive among competitors, and Porter's analysis demonstrated that the essence of strategy is the choice to perform activities differently from the others. Therefore, the need of solutions to improve performance in various levels combined with technologies is a key factor for success.

In this context, the purpose of the present paper is to investigate how machine learning has supported operations strategy in organizations focusing on Slack's (2009) performance objectives: cost, speed, quality, flexibility and dependability. Among Slack's performance dimensions (2009), cost is the direct competition on rates while speed is the turnaround time between customers ordering a product or service and the point at which they receive it. Quality is the visual aspect of how well an operation does what it does. Dependability means that customers can rely on organization to receive their goods exactly when expected and finally, flexibility is the ability to change an operation to match customers' requirements. Since the dimensions influence positively or negatively on each other, the present study also analyzes an integration of performance objectives, comparing and relating their multiple gains, despite the tradeoffs.

Regarding the paper structure, Section 2 introduces a brief theoretical background of operations strategy and machine learning. Section 3 details the research design, which consists on the search terms for the paper selection on Scopus database. Sequentially, Section 4 brings the results, which are segmented by two subchapters, the selected papers with their content analysis and a following operations strategy matrix to allocate them in Slack's competitive advantage pillars. Finally, Section 5 presents the conclusions, addressing limitations and further research.

2 Literature review

This literature review presents firstly a brief theoretical background of operations strategy along with a following machine learning overview.

2.1 Operations strategy

In a decade of high manufacturing processes, the companies need to stand up for their competitors. Porter (1996) once said the only way to outperform is by preserving competitive advantages. These advantages are grounded by the costumers needs and are related to the continuous improvement methods applied on quality, flexibility, cost, time and productivity (Slack *et al.*, 2009). Focused on the core business, costumers and the companies' competitive advantages meet to perform strategically trying to achieve every aspect of improvement in order to reach exceptional performance. Strategy is essential for the competitiveness and according to Porter (1996), the competitive positioning is a matter of choosing the right factors to focus on, applying trade-offs.

Strategy is related to the company's plans, ploy, patterns, position and perspective (Mintzberg, 1987). Operations strategy develops internal guidelines to deal with the competition and the market threats, creating patterns to establish the intended company's behavior. Traditional strategy management has been challenged due to organizational competitiveness, demanding new frameworks and models considering the relationship between roles, capabilities and design theoretical recommendations for a performance measurement system (Pinheiro de Lima *et al.*, 2008).

Strategy purpose is to demonstrate how well grounded is the management process, its influence on the organization position on a specific market and the perspective sets of the internal characteristics of the company (Bititci *et al.*, 2011).

All these definitions guide the organization to achieve its unique strategy, which provides the necessary differences to reach competitive advantages with faster results (Bititci *et al.*, 2011). However, defining a strategic process plan is not an easy task and cannot be static (Hayes, 1985). Once the company's strategy is created, it has to be continually analyzed to identify its efficiency and evolution. Nelly (2006) shows the relationship between strategy and performance gains, concluding that the strategy objectives in action can bring not only unique performance results, but also a combination of categories, like cost and quality. As the competition arises, the competitors tend to find new ways to compete and the managers need to choose new trade-offs to shape the strategy plan. Hayes (1985) highlighted that the company has to establish its corporate goals, find alternative paths to achieve these targets and marshal what is necessary in capabilities to implement and follow defined strategies. Even so, easy-ways-means method itself does not guarantee organizational performance, since the strategy happens in the long-term with all employees playing a respective role in its work execution and developing their proper capabilities strengthen the competitive strategy (Skinner, 1969). Okoshi *et al*. (2019) have recently found performance results depend on policies and capabilities that are addressed and managed by companies' decision areas.

Personal capabilities and competitive technologies are some key recourses for outstanding performance, once they can possibly be unique and not easily copied by competitors (Hayes and Upton, 1998). This approach focusses on innovative operation tools and it has been enhanced by this new technological era. Within Industry 4.0 context, artificial intelligence reinforces operational advantages with a faster and more reliable work execution. However, the benefits are not exclusively limited to shop-floor and operational activities, since data science is an inter-disciplinary field that uses not only scientific methods and processes, but also algorithms and systems to extract knowledge and insights from structured and unstructured data (Moorthy and Gandhi, 2017). Therefore, competitive indicators together with consistent advanced knowledge are also provided by artificial intelligence, bringing important relevance for strategy definitions. In this context, the present study links machine learning to organizational strategic goals.

2.2 Machine learning

Performance fulfillment has a high value service that goes beyond management and control, enabling communication, roles and informational skills to translate the strategy and challenge predefined concepts by senior leadership (Neely and Alnajjar, 2006; Pinheiro de Lima *et al*., 2008). Machine learning has been used as a tool to provide this meaningful knowledge. However, most of the frameworks postulating the best practices, which should be adopted in performance analytics projects, do not involve the respected data complexity. In this context, Dutta and Bose (2015) developed a new framework with the purpose to provide organizations a holistic roadmap in conceptualizing, planning and successfully implementing Big Data projects. The procedural steps involve a step-by-step project map with a cross functional project team, adoption of innovative visualization techniques, and a consistent top management commitment to data driven decision making.

Machine learning is an interdisciplinary research area, which combines ideas from several branches of science namely, artificial intelligence, statistics, information science, mathematics and many others. The main purpose of machine learning approach is on the development of fast and efficient learning algorithms that can make predictions on data (Moorthy and Gandhi, 2017). Therefore, machine learning is also known as predictive analytics, which aims to determine what is likely to happen in the future. The predictions are based on statistical techniques that fall under the general category of data mining (Ouahilal *et al.*, 2016). This quantitative accuracy for predictions is extremely important for an assertiveness in decision-making processes, although the computational time of the algorithms are critical in terms of cost and project viability (Moorthy and Gandhi, 2017). In this digital era context, a recent study revealed real-time data, connectivity and interoperability are some of the most important key factors for a successful digital manufacturing adoption (Da Silva *et al*., 2019)

Machine learning projects have been increasingly managed by healthcare environment, providing accurate diagnosis, helping to predict cancer, chronic kidney disease (Charleonnan *et al.*, 2016) and even the effectiveness of music therapy (Raglio *et al.*, 2020). However, its multidisciplinary has also reached sport analysis, quantifying the relation between performance and success in soccer (Pappalardo and Cintia, 2018) and the educational setting, predicting academic performance with matriculate score and previously semester and pre-university exams as predictors' variables (Halde *et al.*, 2017). Organizational field was not left behind. Some companies have applied artificial intelligence for customer retention (Sabbeh, 2018), identify potential customers based on purchase behavior (Choudhury and Kur, 2019) and even employee performance prediction through historical datasets (Jayadi *et al.*, 2019) This study consists on analyzing how machine learning has contributed to operations strategy pillars defined by Slack *et al.* (2009).

3 Research Design

The research design consisted on a Scopus' search following the initial ProKnow-C steps for axes' definition, although our portfolio composition consists of exclusively five papers in a first iteration (Ensslin *et al*., 2010). Machine learning and operations strategy themes were searched with the reunion of 1st and 2nd axes linked by Boolean Operator "AND", as presented by Figure 1.

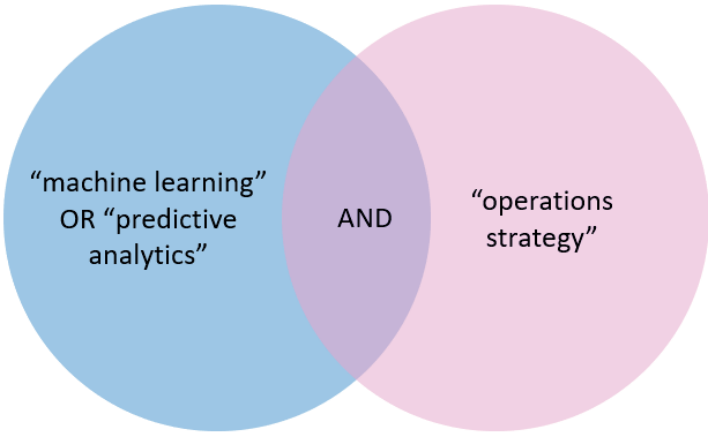

Figure 1. Search terms.

The search expression was limited to title, abstract and keywords. Only open-access papers written in English were searched and relevance filter was applied, as presented by Figure 2.



Figure 2. Search methodology.

Scopus presented 1293 papers and adherence test as applied to certify the assertiveness of search terms. On the following step, only high impact journals were included, rejecting 897 and resulting in 396 papers. Finally, as authors, we selected five machine learning studies that directly addressed each of Slack strategic pillars based on title and abstract details.

4 Results

Five papers published in high impact journals were selected from our Scopus search for our content analysis of their respective machine learning projects through Slack's strategic pillars (2009), as presented in Table 1.

Table 1. Machine learning selected studies.

	MACHINE LEARNING STUDIES OVER STRATEGY PILLARS	CITATIONS	JOURNAL H-INDEX
COST	LOYER, J. L.; HENRIQUES, E.; FONTUL, M.; WISEALL, S.: Comparison of Machine Learning methods applied to the estimation of manufacturing cost of jet engine components. International Journal of Production Economics, v.178, p. 109–119 (2016).	57	172
SPEED	CAVALCANTE, I. M.; FRAZZON, E. M.; FORCELLINI, F. A.; IVANOV, D.: A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. International Journal of Information Management, v.49 (n. March), p. 86–97 (2019).	49	99
QUALITY	CORREA, M.; BIELZA, C.; PAMIES-TEIXEIRA, J.: Comparison of Bayesian networks and artificial neural networks for quality detection in a machining process. Expert Systems with Applications, v.36 (n.3 pt.2), p. 7270–7279 (2009).	194	184
FLEXIBILITY	SUSTO, G. A.; SCHIRRU, A.; PAMPURI, S.; MCLOONE, S.; BEGHI, A.: Machine learning for predictive maintenance: A multiple classifier approach. IEEE Transactions on Industrial Informatics, v.11 (n.3), p.812–820 (2015).	273	115
DEPENDABILITY	KO, T.; HYUK LEE, J.; CHO, H.; LEE, W.; LEE, M.: Machine learning-based anomaly detection via integration of manufacturing, inspection and after-sales service data. Industrial Management and Data Systems, v.117 (n.5), p.927–945 (2017).	14	96

The selected bibliographic portfolio presents only high impact journals with considerable impact on science community.

4.1 Content analysis

This section presents a brief content analysis of the selected studies, identifying their respective strategic achievements.

•Study 1 – Cost

A cost management project of the manufacturing sector was applied using a comparison of machine learning approaches to estimate the cost of jet engine components. Production volume and material cost itself were some of the predictor variables in the dataset composition. Loyer et al. (2016) applied five distinct algorithms and followed the machine learning literature in terms of predictive accuracy, goodness-of-fit, and also aspects as interpretability and computational time. Gradient Boosted Trees and Support Vector Regression presented superior accuracy and the best execution time, compared to all the other methods. On the other hand, Multiple Linear Regression, the worst performed algorithm in terms of accuracy, presented the best interpretability and easiness to fit and train. The study proved machine learning is an effective, affordable and competitive approach for statistical cost modelling in manufacturing processes. It is noticeable that cost is the main target of the study, but in the long term, Loyer et al. (2016) defend the cost estimation could be part of a decision system used by industrial engineers to identify outlier components. Hence, the benefits can be enhanced by the whole supply chain system, providing more flexibility and quality in

operations. A further research was addressed to apply the same analyses with other jet engine parts to certify whether the conclusions remain valid in other scenarios.

- **Study 2 – Speed**

Cavalcante *et al*. (2019) proposed a supplier selection model using supervised machine learning. The authors considered supplier performance data with delivery date and quantity delivery to predict supplier dependability with on-time delivery, together with a make-to-order simulation model that involved suppliers, internal material flow and delivery forecasts to customers. Regarding to machine learning techniques, random forest, linear regression and k-nearest neighbors were performed along with hybrid algorithms. The combination of both approaches brought risk mitigation strategies in supply chain management. The redesign of supplier base and supplier investment analysis are an important contribution. Complementarily, the digital scope of machine learning and simulations provide a digital manufacturing analysis, enhancing a consistent velocity gain and cost reduction with a better supplier portfolio management. The study, however, needed to leave behind some estimations of probabilities of highly unpredictable events to take advantages from smart manufacturing data to predict supplier proneness to disruptions.

- **Study 3 – Quality**

Machine tool automation for quality defection improvement in manufacturing segment, can promote higher quality products in order to achieve competitive advantages. A case-study was investigated by Correa *et al*. (2009) on a machine learning project where surface roughness was defined as a predictive indicator for quality predictions. The researchers compared Bayesian Networks (BN) to Artificial Neural Networks (ANN) and tried a variety of measures and models with the same dataset, and as a result, Bayesian networks presented a superior assertiveness on quality prediction. It is important to recognize that this machine learning application is not limited to reinforce higher quality products, but also to provide a reduction in production time, since it also promotes a reduction in operational time with under-quality products and enhances speed with a faster work time in operations. These solutions proved to increase quality results on a very high level, but also request a distinguished expertise on the BN and ANN algorithms.

- **Study 4 – Flexibility**

A predictive maintenance case-study project was applied with a multiple classifier machine learning method. Since maintenance issues are unstable, it is a challenging task to find the best quantifying measures to predict failure risks and costs with assertiveness. Therefore, Susto *et al*. (2015) proposed a training algorithm of multiple classification modules with distinct prediction approaches to provide performance tradeoffs on frequency of unexpected breaks and unexploited lifetime. The authors successfully applied their proposed method in a semiconductor manufacturing company, where the chosen process was the replacement of tungsten filaments used in ion im-

plantation, one of the most critical processes in semiconductor industries. Some of the predictor variables were pressure, position and quantity of electric charge. Support vector machines and k-nearest neighbors were the two chosen algorithms to perform, and the multiple machine learning classifiers working in parallel provided predictive knowledge to improve decision-making and feed the maintenance management system, to minimize downtime and its costs. This method highlights the improvements on flexibility and cost reduction which for Susto et al. (2015), can be even better when a second training iteration is applied minimizing the whole operating costs. Nevertheless, flexibility is an important achievement, from a lower downtime to an efficient maintenance management, in which operations become consequently faster and more flexible.

- **Study 5 – Dependability**

The degree of reliable products and processes brings critical indicators of a well performing industry, since they demonstrate the control and analysis of parameters in the production process. In some cases, the last step for product inspection is made by a cold test and trials, but even with all the applied control, a defect can appear only when the product is operating at a costumer. Ko *et al*. (2017) demonstrate a case study of an automated analysis tool, providing better product dependability using Lenzerini's formula combined to binary genetic algorithm-based wrapper approach. The case was applied using alter-sales service data from a heavy machine industry, which could identify engines with high probability defects before shipping the products to customers. This method highlights the importance of applying machine tool automation to increase dependability while reducing extra costs on the number of inspected items, human resources, and consequently, on the efficiency. Moreover, the case study also suggests that further studies need to be made so the machine learning model can find defects earlier than what was proposed using quality data from the machines' suppliers and the whole manufacturing process.

4.2 Operations strategy matrix

An operations strategy matrix analysis, presented by Table 2, was built based on a relation of the previous content analysis through Slack *et al.* (2009) strategic pillars.

Table 2. Operations strategy matrix analysis.

	COST	SPEED	QUALITY	FLEXIBILITY	DEPENDABILITY
Study 1	x		x	x	
Study 2	x	x			x
Study 3	x	x	x		
Study 4	x	x		x	
Study 5	x		x		x

The present classification is given by the authors based on the previous content analysis, since it was perceptible that machine-learning projects brought competitive advantages in at least three of the five strategy dimensions of Slack's literature. It was noticeable that even if the project was designed to follow a single dimensional specific target, it supported some extra strategic advantages in the long term. Additionally, cost reduction was an important achievement obtained by all the selected studies, which made convenient a visual understanding of the interrelationship among the strategic pillars achieved by the analyzed studies, presented by Figure 3.

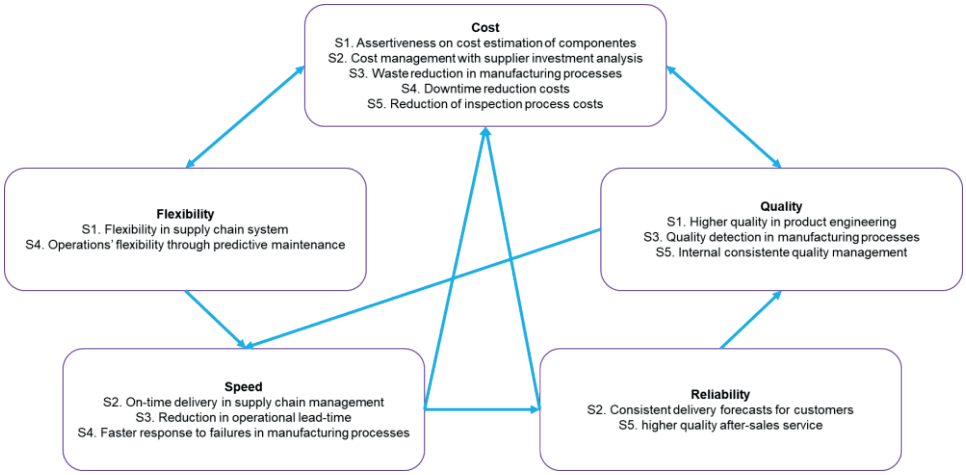

Figure 3. Interrelationships among strategic pillars.

The interrelationship illustrated reveals that only cost-flexibility and cost-quality have a mutual impact on each other, since all others present a single direction impact on another. Machine learning approaches of all studies had an impact on cost, even as a secondary competitive target or not specifically intended on their respective projects.

Quality strategic achievement was also meaningfully interrelated, reinforced by the implementation of a more consistent quality management of product engineering on Study 1 and a much more efficient quality inspection process provided by Study 5 after-sales service data. Speed, analyzed by Study 2 project, plays also a substantial role on influencing dependability for customers through on-time delivery together with a more consistent cost management of suppliers. Additionally, speed in operations is strengthened when a quality management or a predictive maintenance project is applied, as did Study 3 and 4, respectively.

The interrelationship among strategic pillars summarizes machine learning integration with operations strategy. Once the projects achieve better quality and make operations more efficient, they provide better economical results reaching cost and flexibility through accurate predictions of work execution. Therefore, depending on the

project context and its strategic directions, dependability can also be part of the competitive advantages in the medium to long-term.

5 Conclusion

This paper presents a simple and consistent preliminary investigative overview of how machine-learning projects have helped organizations to achieve consistent competitive advantages in many different dimensions.

The interrelationship analysis has indicated cost as the common achievement of all analyzed studies while flexibility and dependability are connected to others although with a less significant interrelationship. This event can possibly be explained by the fact that these both dimensions are often only reached in the long-term, but this is a preliminary hypothesis that demands further investigation.

We have contributed to reinforce machine learning, an important subfield of artificial intelligence, as a strategy key to organizational environment with our content analysis. The built of a matrix perspective over Slack's pillars can also be used as a guidance to collect additional studies of machine learning projects. This is the following step, since limitations of the present study are related to its small bibliographic analysis. We expect to extend this preliminary investigation to offer deeper conclusions with the expansion of our proposed interrelationship analysis. Another important limitation to address is that the present initial analysis was made according to authors' content analysis, so another further research step is a taxonomy application to reinforce our findings with an extension of the portfolio.

Another important further research is to go beyond the expansion and the taxonomy, and conjointly relate the decision organizational areas that provide the capabilities that needs to be mobilized in process that enable project results.

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A Database Curation for Prediction of the Refractive Index in the Virtual Testing of Polymeric Materials by using Machine Learning.

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Abstract. The aim of industry 4.0 is to promote productivity and innovation by incorporating emerging IT technologies, where machine learning is playing a central role in this industrial revolution. In this sense, the production of new materials could take advantage of novel virtual testing approaches based on data science for supporting the design of new polymers. Nevertheless, the lack of data for learning virtual testing models constitutes a hard challenge for progressing in these innovative techniques. Therefore, it is especially important to create reliable databases for polymer study and make them available to the scientific community. In this work, we have focused on the generation of a trustworthy database of Refractive Index (RI) of synthetic polymers. This paper details the different types of errors found in the data source and the corrections made during the curation and cleaning of this database. Additionally, some Quantitative Structure-Property Relationship models for predicting RI, inferred without domain expert intervention, are presented and discussed for illustrating how virtual testing can be applied using this database.

Keywords: Refractive Index, Machine Learning, Polymer Database.

1 Introduction

At present, the world industry is going through a new revolution, known as Industry 4.0, which combines advanced production and operation methods with smart technologies that are integrated into organizations, people and assets. This revolution is driven by emerging new technologies such as artificial intelligence, big data analytics, nanotechnology, robotics and the Internet of Things (IoT), among others.

Consequently, organizations must recognise the technologies that best meet their needs to capitalize in them, because companies that do not understand the evolution and opportunities in business that Industry 4.0 brings are at risk of dropping market share. In this context, technologies based on machine learning are playing an important role in the innovation of production processes and, in particular, are having a huge impact in the discovery of new industrial materials [1].

A traditional project for development of new materials follows three main phases: design, synthesis and testing. During the first phase, different alternatives prototypes are designed for the potential new material. This design is guided by domain experts, which pursued some specific characteristics related to required industrial use for the future material. Then, the new materials are synthetized by polymerization reactions. Finally, specimens (physical samples) of them are tried by typical laboratory tests used in polymer science, such as the tensile test, in order to evaluate which polymeric material fulfil the desired industrial profile. Nowadays, this traditional process has been improved by the use of virtual testing models derived from machine learning methods [2]. Figure 1 illustrates how the use of virtual tests is being incorporated in the traditional process. This virtual testing phase makes it possible to predict relevant properties of the alternative prototypes even before synthesizing them, helping to prioritize the best candidate prototypes for the next steps of the polymer development project. Additionally, as a result of virtual testing, it is possible to rethink some design decisions and iteratively reformulate the original prototypes before moving to the more expensive phases of the project, thus saving money, resources and time [3].

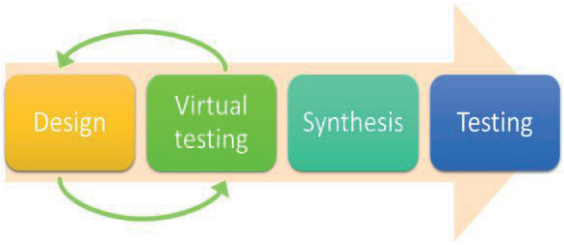

Fig. 1. Incorporating virtual testing in a traditional project for development of new materials.

These virtual tests are generated as Quantitative Structure–Property Relationships (QSPR) models inferred by supervised learning methods. In Polymer Informatics, QSPR models usually are regression models where a subset of molecular descriptors (*features*), which characterize the chemical structure of the molecules, are used for predicting the value of a target property under study. Figure 2 shows the sequence of steps for obtaining a QSPR model. First, the database to be used for learning the model must be defined and revised. In this step, it is important to revise that all required pieces of information be available for each polymer included in the database (polymer structure along with its corresponding Simplified Molecular Input Line Entry Specification (SMILES) code and the experimental value of the target property). If inconsistencies or mistakes are detected during this revision, a curation and cleaning step must be conducted in order to obtain a trusty database. After that, QSPR models can be inferred applying to main procedures: feature selection, where the most relevant

molecular descriptors for target property are identified, and models inference, where alternative QSPR models are generated by supervised learning methods. Lastly, an external validation of the models is executed for selecting the best QSPR models trying to avoid overfitting and correlations by chance.

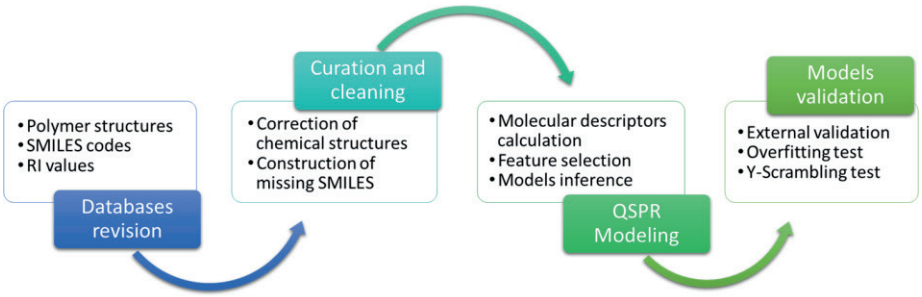

Fig. 2. Steps for generating a QSPR model for virtual testing.

Unfortunately, although this novel proposal can help to speed up the development projects of new polymers by supporting the design stage, the lack of data is slowing the progress and adoption of this innovative technology [3, 4]. Addressing this need, the "Materials Genome Initiative" was created in 2011, involving multiple US agencies collaborating to create policies, resources, and infrastructure that would support US institutions as they worked to rapidly discover and manufacture advanced materials with low cost [5]. Therefore, it is imperative to create reliable databases and make them available to the scientific community for supporting the incorporation of virtual testing in the polymer industry.

In this work we have focused on the generation, curation and cleaning of a database of Refractive Index (RI) of synthetic polymers, which is used in Quantitative Structure-Property Relationship (QSPR) predictive modelling. This property has special interest in the design of optical fibres, which combine two materials with different RI values: high RI (in core) and low RI (cladding). Although some databases that contain several polymers, together with their chemical structures and RI values, can be found in the literature, we have detected several mistakes and inconsistencies that must be corrected [6]. Besides, the repeating unit structure of the polymers and their computational representations in SMILES code are needed for QSPR modelling. Therefore, this report details the different types of errors found in the data source and the corrections made as part of the revision, curation and cleaning of this RI database. Finally, in order to illustrate the use of the RI database in virtual testing, the results of preliminary QSPR models generated by machine learning, without domain expert intervention during the modelling step, are presented and discussed.

Materials and Methods

1.1 Databases: curation and cleaning

Database Sources.

We have used the database reported by Jabeen et al., [6] for the purpose of making a fair performance comparison of our QSPR models with his reported model. This database contains 127 polymers, with their experimental RI values. However, during the database revision, we found some inconsistencies in terms of structure, property values and chemical names, so we began a process of curing and cleaning. To perform this cure, it was necessary to verify the data with other sources [7-12].

Data curation and cleaning methodology.

Data cleaning consists of detecting and correcting or removing incorrect or corrupt data from a database. We did a review of the database reported by Jabeen, collating the RI values and the polymer names with the databases reported by Bicerano [7], Duchowicz et al., [8], Xu et al., [9], Khan et al., [10], Seferis [11] and the chemical structure with PubChem [12]. Additionally, the database reported by Duchowicz was used for obtaining the SMILES codes, which are necessary for computing the molecular descriptors required for training our QSPR models. However, not all polymers were found in the Duchowicz's database, then the rest of the molecule SMILES codes were created by using Molinspiration Galaxy 3D Structure Generator tool [13].

During the review process of the Jabeen's database we found inconsistencies related to the polymer structures. Furthermore, some of them did not correspond to the reported name, and we also found some duplicate polymers. In this sense, we proceeded to make a structure correction due to the inconsistencies that we found and, additionally, we proceeded to develop the missing SMILES codes. Figure 3 shows the steps to curate the database. First, we have made a general revision of the reference database [6], checking polymer names, RI values and chemical structures. The second step was to carry out a detailed verification of each one of the structures, corroborating them against PubChem [12] and Sigma-Aldrich Product Catalog [14]. Since during the verification some errors were found in the structures, the third step was carried out by correcting the structures according to the information collated from the previous sources (Further explanation and examples of this step can be found in section 3.1). Then, in the fourth step, the property values were reviewed according to those reported in the databases of Bicerano [7], Duchowicz et al., [8], Xu et al., [9], Khan et al., [10], and Seferis [11]. After finding some errors, we proceeded to the fifth step, where they were corrected by homogenizing all RI values to four corrected decimal places. In the sixth step, we have made a revision of the SMILES associated with the polymers structure that we need to perform the cure. This revision was carried out by visualizing and verifying that the SMILES code of each polymer was structurally correct. For this, we have used the Molinspiration Galaxy 3D Structure Generator tool [13], which allows to obtain a visualization of the molecule corresponding to a certain SMILES code. In the seventh step, seeing that not all of the polymers reported by Jabeen et al., [6] were contained in the Duchowicz's database [8], we proceeded to develop the missing SMILES. Finally, in the eighth step, we have made a revision of the already curated database, visualizing

and checking that everything - i.e. polymer name, polymer structure, SMILES code, and RI value - is matching for each polymer.

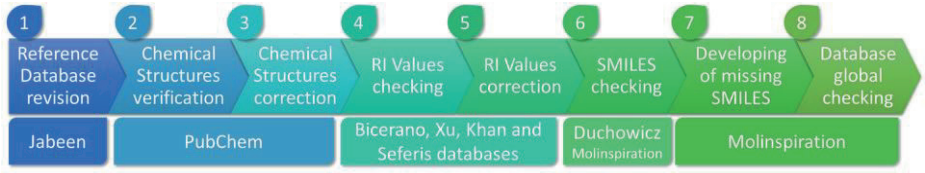

Fig. 3. Steps for the database curation process.

1.2 QSPR Modelling

Feature Selection.
The feature selection was made with the WEKA tool [15], using fixed seeds randomization in order to ensure reproducibility and default settings. For this purpose, several well-known methods were used to obtain a total 6 different subsets of molecular descriptors using 75% of the database (training dataset). The methods used were Correlation-based Feature Subset Selection (CFS) and Wrapper Subset Eval (WSE). The last feature selection method evaluates attribute sets by using a learning scheme. In particular, in this work, WSE was defined using different learning techniques: Linear Regression (LR), Neural Networks (NN), Random Forest (RF), Random Committee (RC), and K-Nearest Neighbours (KNN).

QSPR Models Inference.
To carry out the learning process and structure-activity modelling 5 different machine learning methods have been used on each subset: Linear Regression (LR), Neural Networks (NN), Random Forest (RF), Random Committee (RC) and K-Nearest Neighbours (KNN). Therefore, a total of 5 putative QSPR models were generated from each subset. The WEKA [15] implementation of each method was used.

We select one QSPR model for each subset for the next instance. The criterion to select the models is to keep the QSPR model with the highest R^2. This metric is used because it is the same reported by Jabeen's model [6] that will be used as reference performance in our work.

QSPR Models Validation.

External Validation. The goal of any machine learning algorithm is to learn a generalizable knowledge. Generalizability is the capability of the model to adapt appropriately to previously unseen data, but similar as that used to create the model. Underfitting occurs when the model does not fit the data well enough, and overfitting occurs when a model captures the noise of the data. External validation was performed in this work using the remaining 25% of the molecules in the database (validation dataset). In addition, we also used Roy's method [16] for classifying the QSPR models according to the quality of their predictions (Good, Moderate or Bad).

Chance correlations test. There is a risk of finding random correlations in QSPR modelling. Therefore, it is desirable to perform tests showing the performance of models built with the same target values but randomly permuted. Thus, the performances of the models fitted for random procedures should be much lower than the QSPR models obtained from the original target values [17].

2 Results and Discussions

2.1 Data Curation & Cleaning.

The importance of database quality used in supervised learning lies in ensuring that the information is adequately collected and curated. Therefore, a reliable dataset constitutes the key foundations for a meaningful knowledge extraction process. At the end of the learning process, the model is capable of mapping the input data (molecular descriptors) to the output data (target property) in a trustworthy way.

Despite the great effort involved in creating a new database, mistakes are often observed since the creation process is a manual one subject to human error. One of the main problems found in the database reported by Jabeen et al., [6] were the inconsistencies in the structures, and the IDs of the polymers also did not match with the IDs of the existing structures in the supplementary material.

A detailed revision of each polymer was performed. We found mistakes in 21 molecules of Jabeen´s database [6], but we will illustrate the curation and cleaning process only explaining a few representative cases. For example, we found that the Poly[oxy(methyl n-octadecylsilylene)] was duplicated but with different RI values, so we decided to solve this inconsistency by keeping the RI value reported in Bicerano's database [7]. Besides, we found that 16 polymers presented in Jabeen's database [6] contained errors in their chemical structure. For example, the Poly(2-ethoxyethyl acrylate), i.e. ID 37 in Table 1, lacked a carbon in the structure, therefore we added the missing carbon and developed the corresponding SMILES code. Figure 4 shows the structural difference.

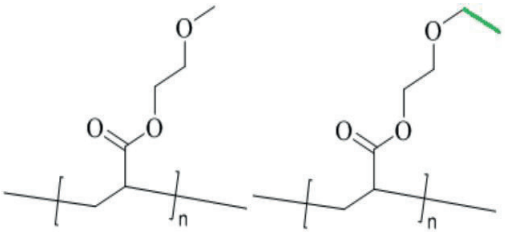

Fig. 4. The original structure is shown (left) and on the right the added carbon in green.

In all the cases that we had to correct the SMILES code, the Molinspiration Galaxy 3D Structure Generator tool [13] was used. For example, in the case of ID 37, which is poly(2-ethoxyethyl acrylate), we create the SMILES code: CCOCCOC(=O)CC, as shown in Figure 5.

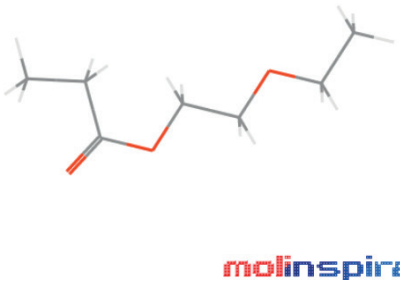

Fig. 5. The Poly(2-ethoxyethyl acrylate) represented by Molinspiration Galaxy 3D Structure Generator. The resulting SMILES code is as follows: CCOCCOC(=O)CC

Figure 6 shows the Poly[oxy(methyl n-octadecylsilylene)], i.e. ID 11 in Table 1. In this case, we verified that a carbon atom was wrongly located in the chemical structure. The carbon indicated by the cross was correctly relocated (highlighted in green). The resulting SMILES code is O[Si](C)(CCCCCCCCCCCCCCCCCC).

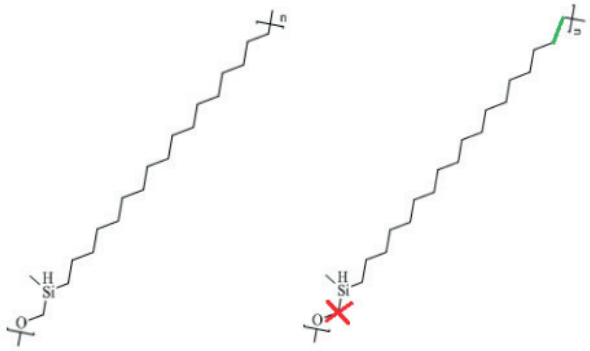

Fig. 6. On the left the original structure for Poly[oxy(methyl n-octadecylsilylene)] is shown and on the right its correction.

Regarding the RI values checking, we detected in Jabeen's database that several polymers with different structures have the same property value, which is an undesirable behaviour to QSPR modelling. For this reason, we looked up the RI values in the literature [7, 9-11], and we realized that the target values must be represented with four decimal places in order to denote those structural differences. Therefore, we have updated the property values, so now it is possible to differentiate the RI values for polymers with structural differences such as pairs ID 21-22, ID 25-26, ID 31-32, ID 46-47, ID 52-53, ID 69-70, and others. Figure 7 shows the structural representation of the polymers ID 46 (Poly (ethylene)) and ID 47 (Poly (2-fluoroethyl methacrylate)), where it can be seen that their structures are significantly different. Both have the same property value (1.476) in Jabeen's database, however, adding the fourth decimal place -taken from literature-, the difference in the property value can be appreciated (1.4760 and 1.4768 respectively). Finally, after a global and detailed checking, 126 polymers were included in the resulting database and used for QSPR modelling (see Table 1).



Fig. 7. Structures of two polymers: on the left the ID 46 and on the right the ID 47.

Table 1. Curated database of Refractive Index (RI) for 126 polymers.

ID	Name	RI
1	Poly(hexafluoropropylene oxide)	1.3010
2	Polytetrafluoroethylene	1.3500
3	Poly(trifluorovinyl acetate)	1.3750
4	Poly(pentafluoropropyl acrylate)	1.3850
5	Poly(dimenthyl siloxane)	1.4035
6	Poly(trifluoroethyl acrylate)	1.4070
7	Poly(2,2,2-trifluoro-1-methylethyl methacrylate)	1.4185
8	Poly(vinylidene fluoride)	1.4200
9	Poly[oxy(methyl n-hexylsilylene)]	1.4330
10	Poly(trifluoroethyl methacrylate)	1.4370
11	Poly[oxy(methyl n-octadecylsilylene)]	1.4430
12	Poly[oxy(methyl n-octylsilylene)]	1.4450
13	Poly(vinyl isobutyl ether)	1.4507
14	Poly[oxy(methyl n-hexadecylsilylene)]	1.4510
15	Poly(vinyl ethyl ether)	1.4540
16	Poly[oxy(methyl n-tetradecylsilylene)]	1.4550
17	Poly(oxyethylene)	1.4563
18	Poly(propylene oxide)	1.4570
19	Poly(3-butoxylpropylene oxide)	1.4580
20	Poly(vinyl n-pentyl ether)	1.4590
21	Poly(3-hexoxylpropylene oxide)	1.4590
22	Poly(vinyl hexyl ether)	1.4591
23	Poly(4-fluoro-2-trifluoromethylstyrene)	1.4600
24	Poly(vinyl n-octyl ether)	1.4613
25	Poly(vinyl 2-ethylhexyl ether)	1.4626
26	Poly(vinyl n-decyl ether)	1.4628
27	Poly(2-methoxyethyl acrylate)	1.4630
28	Poly(tert-butyl methacrylate)	1.4638
29	Poly(4-methyl-1-pentene)	1.4650
30	Poly(3-ethoxypropyl acrylate)	1.4650
31	Poly(n-butyl acrylate)	1.4660
32	Poly(vinyl propionate)	1.4665

33	Poly(vinyl methyl ether)	1.4670
34	Poly(vinyl acetate)	1.4670
35	Poly(ethyl acrylate)	1.4685
36	Poly(3-methoxypropyl acrylate)	1.4710
37	Poly(2-ethoxyethyl acrylate)	1.4710
38	Poly(isopropyl methacrylate)	1.4728
39	Poly(1-decene)	1.4730
40	Poly(propylene) (atactic)	1.4735
41	Poly(vinyl sec-butyl ether) (isotactic)	1.4740
42	Poly(dodecyl methacrylate)	1.4740
43	Poly(ethylene succinate)	1.4744
44	Poly(tetradecyl acrylate)	1.4746
45	Poly(vinyl formate)	1.4757
46	Poly(ethylene)	1.4760
47	Poly(2-fluoroethyl methacrylate)	1.4768
48	Poly(isobutyl methacrylate)	1.4770
49	Poly(methyl acrylate)	1.4790
50	Poly(oxymethylene)	1.4800
51	Poly(n-hexyl methacrylate)	1.4813
52	Poly(n-butyl methacrylate)	1.4830
53	Poly(2-ethoxyethyl methacrylate)	1.4833
54	Poly(n-propyl methacrylate)	1.4840
55	Poly(ethyl methacrylate)	1.4850
56	Poly(3,3,5-trimethylcyclohexyl methacrylate)	1.4850
57	Poly(vinyl butyral)	1.4850
58	Poly(2-nitro-2methylpropyl methacrylate)	1.4868
59	Poly(1,1-diethylpropyl methacrylate)	1.4889
60	Poly(methyl methacrylate)	1.4893
61	Poly(2-decyl-1,4-butadiene)	1.4899
62	Poly(3-methylcyclohexyl methacrylate)	1.4947
63	Poly(4-methylcyclohexyl methacrylate)	1.4975
64	Poly(vinyl methyl ketone)	1.5000
65	Poly(sec-butyl α-chloroacrylate)	1.5000
66	Poly(1,2-butadiene)	1.5000
67	Poly(vinyl alcohol)	1.5000
68	Poly(2-bromo-4-trifluoromethyl styrene)	1.5000
69	Poly(ethyl α-chloroacrylate)	1.5020
70	Poly(2-methylcyclohexyl methacrylate)	1.5028
71	Poly(1,1-dimethylethylene)	1.5050
72	Poly(cyclohexyl methacrylate)	1.5066
73	Poly(tetrahydrofurfuryl methacrylate)	1.5096
74	Poly(1-methylcyclohexyl methacrylate)	1.5111
75	Poly(2-hydroxyethyl methacrylate)	1.5119
76	Poly(vinyl chloroacetate)	1.5130
77	Poly(N-butyl methacrylamide)	1.5135
78	Poly(methyl α-chloroacrylate)	1.5170
79	Poly(2-chloroethyl methacrylate)	1.5170
80	Poly(allyl methacrylate)	1.5196
81	Polyacrylonitrile	1.5200

82	Polyisoprene	1.5210
83	Poly(acrylic acid)	1.5270
84	Poly(1,3-dichloropropyl methacrylate)	1.5270
85	Poly(N-vinylpyrrolidone)	1.5300
86	Poly(cyclohexyl α-chloroacrylate)	1.5320
87	Poly[oxy(methylphenylsilylene)]	1.5330
88	Poly(2-chloroethyl α-chloroacrylate)	1.5330
89	Poly(2-aminoethyl methacrylate)	1.5370
90	Poly(vinyl chloride)	1.5390
91	Poly(sec-butyl α-bromoacrylate)	1.5420
92	Poly(cyclohexyl α-bromoacrylate)	1.5420
93	Poly(2-bromoethyl methacrylate)	1.5426
94	Poly(2-bromoethyl ethacrylate)	1.5426
95	Poly(ethylmercaptyl methacrylate)	1.5470
96	Poly(1-phenylethyl methacrylate)	1.5487
97	Poly(p-isopropyl styrene)	1.5540
98	Polychloroprene	1.5580
99	Poly(methyl α-bromoacrylate)	1.5672
100	Poly(benzyl methacrylate)	1.5679
101	Poly(m-cresyl methacrylate)	1.5683
102	Poly(phenyl methacrylate)	1.5706
103	Poly(2,3-dibromopropyl methacrylate)	1.5739
104	Poly(ethylene terephthalate)	1.5750
105	Poly(vinyl benzoate)	1.5775
106	Poly(o-chlorobenzyl methacrylate)	1.5823
107	Poly(m-nitrobenzyl methacrylate)	1.5845
108	Poly(2-methylstyrene)	1.5874
109	Polystyrene	1.5920
110	Poly(o-methoxy styrene)	1.5932
111	Poly(p-bromophenyl methacrylate)	1.5964
112	Poly(N-benzyl methacrylamide)	1.5965
113	Poly(p-methoxy styrene)	1.5967
114	Poly(pentachlorophenyl methacrylate)	1.6080
115	Poly(o-chloro styrene)	1.6098
116	Poly(phenyl α-bromoacrylate)	1.6120
117	Poly(N-vinyl phthalimide)	1.6200
118	Poly(2,6-dichlorostyrene)	1.6248
119	Poly(chloro-p-xylylene)	1.6290
120	Poly(β-naphthyl methacrylate)	1.6298
121	Poly(2-vinylthiophene)	1.6376
122	Poly[oxy(2,6-diphenyl-1,4-phenylene)]	1.6400
123	Poly(α-naphthyl methacrylate)	1.6410
124	Poly(p-xylylene)	1.6690
125	Poly(α-vinyle naphthalene)	1.6818
126	Poly(N-vinyl carbazole)	1.6830

Molecular Descriptors Computation.
The DRAGON tool [18] was used to calculate 3839 molecular descriptors for each of the 126 molecules in the database. Therefore, a 95% correlation filter was applied to avoid molecular descriptors that provide redundant information. This filter reduced approximately to 82% of all the descriptors. Finally, 690 molecular descriptors that characterize the molecules and integrate the database were included.

In this way, the definitive database contains 126 curated molecules characterized by 690 molecular descriptors. It was split into two datasets, one saved as a training dataset (75%) and the other one saved as a validation dataset (25%). The value range of the property Refractive Index is from 1.301 to 1.683 for this database.

2.2 QSPR Modelling

Feature Selection
A total of 6 molecular descriptor subsets were selected from the initial pool of 690 molecular descriptors by using 6 different methods. In Table 2, all the subsets, together with used methods and cardinalities are listed. The cardinality for all subsets is higher than the reported by Jabeen et al., [6], which is 4. However, a popular rule suggests that there should be at most one descriptor for every five molecules of the dataset used [19]. It is noteworthy that the 6 selected subsets meet this rule, because they are below to 25 descriptors.

Table 2. Results of the Feature Selection process, selection method, and cardinality of the six subsets selected.

Subset	Feature Selection Method	Cardinality
Subset 1	CFS	16
Subset 2	LR	23
Subset 3	NN	9
Subset 4	RF	11
Subset 5	RC	10
Subset 6	KNN	23

QSPR Models Inference.
In total, 30 models were inferred by training each of the 6 subsets with 5 learning methods. In all cases Leave-One-Out (LOO) was applied. In Table 3, the QSPR model with the best performance, in terms of coefficient of determination, denoted R^2, and the learning method used to infer it, are shown for each subset.

In particular, the best models inferred from subsets 2, 3, and 4 achieve performances above 0.90 of R^2 during the training stage. Therefore, we decided to select these models to continue with the next stage.

Table 3. Results of the QSPR Models Inference process to the best models, value of R^2 and learning method employed

Subset	Inference: R^2	QSPR Method
Subset 1	0.8438	RF
Subset 2	0.9750	LR
Subset 3	0.9012	LR
Subset 4	0.9118	RC
Subset 5	0.8608	RC
Subset 6	0.8538	RF

QSPR Models Validation

External Validation. For the three QSPR models selected in the previous stage, an external validation was executed using the validation dataset saved at the beginning of the experimentation for this purpose. In Table 4, the results of the external validation for each model, the gap in terms of R^2 between training and external validation performances, the classification of the predictions according to Roy's Method [16], and the model's cardinality are shown.

Table 4. Results of external validation in terms of R^2, Mean Absolute Error (MAE), R^2 Gap, and the classification of performance by Roy's method (Roy's Class) for each model.

Subset (cardinality)	Validation: R^2	MAE	R^2 Gap	Roy's Class
Subset 2 (23)	0.8694	0.0176	0.1056	Good
Subset 3 (9)	**0.9097**	**0.0181**	**-0.0086**	**Good**
Subset 4 (11)	0.9048	0.0161	0.0071	Good

Considering the performance of the reference model published by Jabeen et al., [6], which reached 0.8820 of R^2 during the external validation and a R^2 Gap of 0.05, we decided to discard the best QSPR inferred from Subset 2. On the other side, both Subset 3 and Subset 4 present similar behaviours in terms of performance, significantly overcoming the reference model [6]. Nevertheless, note that Subset 3 has a negative R^2 gap value. This means that the QSPR model associated with this subset obtained a higher R^2 in the external validation than the obtained in the training. In other words, this model has better generalization than the models learned from Subsets 2 and 4. This could indicate that the Subset 3 is the best alternative for modelling the structure-activity relationship among the 6 subsets.

In addition, considering the errors in the model's predictions, an evaluation MAE-based was carried out following Roy's method [16]. This method classifies the model predictions into three categories: Good, Moderate or Bad. All models were classified as Good (see Table 4). In this case, the Roy method was not helpful in discarding models because they all have the same classification. However, it helps to know that they are reliable predictions.

In summary, a rigorous external validation of QSPR models was properly done, and the model inferred from Subset 3 was selected to continue to the next stage. This decision is supported by two main observations: is the one with the lowest cardinality and has a negative R^2 gap value. In other words, the possibility of overfitting is rejected, because the predictive capability does not fall (in fact it increases) for unknown data (validation dataset). From this point, this QSPR model learned from Subset 3 using the LR method will be denoted as our best QSPR model.

Chance correlation test. Our best QSPR model is chosen for executing the chance correlation test. In this case Y-Scrambling is used, which consists of randomly mixing the Y (target) values. This test was run 100 times, using the molecular descriptors of Subset 3 and LR method, and finally the mean value performance of the QSPR random models trained in these trials is $R^2 = 0.0258$ and the standard deviation is 0.0422. Thus, we conclude that the QSPR model inferred from Subset 3 is a recommendable option for RI prediction, because it overcomes the reference Jabeen's model performance and, also, the risks of overfitting and chance correlation can be discarded. However, our model has a higher cardinality (9) than the Jabeen's model (4), which is a not desirable characteristic because the models that use several molecular descriptors usually have a more complex physicochemical interpretation.

3 Conclusions

The quality of the data to be used in supervised learning processes always has a central impact on the reliability of the models inferred by these techniques. On the other hand, we know that in the field of material sciences the efforts to provide consistent data sources are high. Nevertheless, the integration of results from different experiments is a complex task, where there are multiple factors that lead to the introduction of mistakes. For this reason, even the databases provided by the scientific literature are subjected to rigorous review processes; they may contain inaccurate or wrong data. Consequently, the checking, curing and cleaning of the databases constitute a mandatory step in any QSPR modelling project in Polymer Informatics.

In this work, we have presented a process of curing and cleaning of a database to be used in the QSPR modelling of the Refractive Index of polymers. In this regard, it should be noted that the generality of the steps proposed for this process allows its application to the curing of other databases in Polymer Informatics. In this sense, the importance of physicochemical knowledge was demonstrated to achieve the correction of chemical structures and their corresponding computational representations guided by an expert in the domain. In this way, it contributes to improving the knowledge extraction process, since the final performance of the QSPR models is increased because of the availability of more reliable data, as can be seen in the models reported in this work.

However, although the models that we have obtained using machine learning methods have achieved a promising performance, it is also true that they constitute "black box" models, i.e., models whose interpretability in physicochemical terms is not always easy to establish. For this reason, it would be desirable that a domain expert could intervene in the process of design of the QSPR model being assisted by

supervised learning methodologies. In particular, the use of strategies and tools for active learning may constitute an alternative to take advantage of expert knowledge. In this regard, we plan to use the VIDEAN software [20] in the future. This tool allows us to evaluate the role of alternative subsets of descriptors for the definition of a QSPR model, by using interactive visual analytics. In this way, we can achieve more interpretable models that employ a smaller number of descriptors. Moreover, taking into account the principle of Occam's razor, it is known that the fewer variables used in the definition of a model, the simpler and more generalizable it is the model.

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Big data analytics process architecture for manufacturing industries: a literature review

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Abstract. With the recent advances in automation and information technologies that triggered the ongoing transformation of production systems into cyber-physical systems (CPS), many industrial organizations have been recently adopting data collection technologies to improve the efficiency and effectiveness of their processes. The Big Data Analytics are being used to analyze large amounts of data and help improve different aspects of an industrial operation. As enterprises face challenges such as increasing costs, quality control and operations. Systematizing how to apply data analytics to improve their processes and practices is, hence, a relevant issue. This paper contributes to this by providing an understanding of how to develop a data analytics process management in manufacturing industries. First, it reviews the existing literature related to data analytics, focusing on analysis and information requirements for manufacturing process and framework. Second, it discusses the major functionalities of data analytics process presented in the literature review, focusing on features that are useful for process management. Finally, it presents and discusses the implications for future research of a conceptual framework for the definition of data analytics process management.

Keywords: Big Data Analytics, Data Analytics, Process Architecture BDA, Operations Strategy

1 Introduction

With the recent advances in automation and information technologies that triggered the ongoing transformation of production systems into Smart Manufacturing based on cyber-physical systems (CPS) and implementation of Internet of Things (IoT), many industrial organizations have recently adopted data collection technologies to improve the efficiency and effectiveness of their processes. Also, with the growth of available data in industrial organizations data analytics has played a major role on manufacturing process, creating challenges for people and machines for data gathering, preparation, analysis and visualization.

The implementation of Big Data Analytics (BDA) in manufacturing processes has potential performance benefits in customer satisfaction, operation expenses and productions productivity [1]. According to Platts, operations managers need to formulate strategic manufacturing planning to achieve enterprise goals, each enterprise has diverse operation practices, but there are four features characteristics of robust and successful methodologies for operations management: procedure, participation, project management and point of entry [2]. Also, to reach operations management goals, organizations need an accurate and efficient performance indicators to guarantee that data gathered is transformed in usable information. According to Bourne et al., based on a study presented by Pettigrew, to generate an accurate performance indicator is important consider organizations fundamental resources for performance indicators development that are concept, context and process. [3] Big Data Analytics aims to assist business organizations to achieve improved understanding of data, and thus, make efficient and well-informed decisions. However, implementing Big Data Analytics at industrial operations is hazy and depends on each scenario and technology used. It is also important having a well-defined systematic architecture design for Big Data Analytics that comprises modern and legacy systems as presented in the studies of [4][5].

This paper contributes by providing an understanding of how to develop a prescriptive data analytics process management in manufacturing industries. Considering the operations strategy indicators performance analysis, based on [2] and [3], using the main concepts of Pettigrew.

First, it reviews the existing literature related to data analytics, focusing on analysis and information requirements for manufacturing processes using the systematic literature review framework called Proknow-C. Second, it discusses the major functionalities of data analytics process by presenting what is available in the literature, focusing on features that are useful for process management. Third, it presents and discusses the implications for developing a data analytics architecture and recommendations with a framework considering data analytics stages and tasks. Finally, concluding with a conceptual framework based on literature review for the definition of data analytics process management.

2 Research Design

This section presents recent research findings in terms of approaches and principles for big data analytics process in industrial organizations and it discusses current practices.

Developing an architecture for data analytics process is complex and diversified. Understand requirements, tools and perspectives from literature is fundamental. Thereby, for this purpose we develop a literature review that follows the steps of the method Proknow-C. According to Afonso et al. [6], Proknow-C literature review framework consists of systematic steps of the literature review in order to have a better portfolio of scientific documents, providing a structured and rigorous procedure, which minimizes the use of randomness and subjectivity in the process of literature review.

The first stage of the literature review consists on defining areas of research interest. In this research, we focused on data analytics architecture and process so we use the

main areas as Data Analysis, Industrial Process Management and Process Architecture. Then, the next stage of the research is to define the research string and databases. Considering the previous stage we define main search keywords to construct the string that is (("" Big Data "OR" Analytics "OR" BDA ") AND (" Architecture "OR" Framework "OR" Method "OR" Method "OR" Procedure "OR" Process ") AND (" Manufacturing ")). With a definition of the string, it was possible to define a database to the literature research; we used Web of Science and Scopus. Considering those databases, we start the research considering documents written in English and excluded repeated documents, which resulted in 2308 documents. Subsequently we selected documents that have title and abstracts in line with BDA or data analytics process architecture research, which resulted in 203 documents. Considering that batch of documents, we develop a document classification of scientific recognition based on document citation impact. Applying this classification analysis to the documents we found out 62 documents including book chapters, scientific articles, conference papers and journals with a considerable scientific recognition. The distribution of the documents by year are presented in Figure 1.

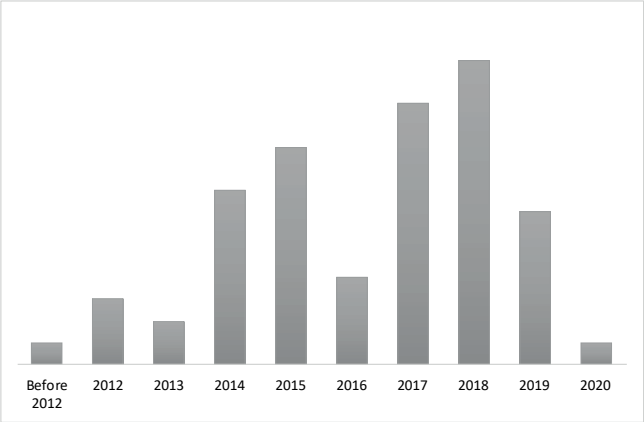

Fig. 1. Distribution of 62 papers by year.

Thereat, to develop a literature review focused on data analytics process architecture; we analyze documents content and context to guarantee that the documents are in accordance with the study. Considering the methodologies for manufacturing strategies formulation, we develop a scientific literature review and use a classification of operations performance strategy concepts based on [2] and [3]. According to the authors, to develop a process architecture it is important to consider strategic operational concepts, as well as company performance indicators. In addition, operations managers need to formulate a strategic manufacturing plan to achieve organization objectives, considering that each company has its different practices to operate.

According to Platts [2], there are four main features characteristics of robust and successful methodologies for operations management, that are: procedure, participation, project management and point of entry. In addition, another highlight to consider in data analytics process architecture is to develop intuitive and accurate performance

indicators. As presented by Bourne et al., based on Pettigrew concepts, the organization fundamentals resources to develop performance indicators are: concept, context and process. To validate the documents considering operations management strategy and performance indicators we develop a matrix using this two concepts based on area of the study [3].

First, we analyze the 62 documents and select each area of data analytics process architecture that was classified in Process Architecture BDA, Process Architecture and Data Analytics, Theories of BDA and Simulation. We consider items that are treated as data analytics process architecture, and if those architecture and process includes concepts of BDA. Thus, on the second step we follow the context of operations strategy and performance indicators, we define the context of the documents, considering if is a theoretical, hypothetical or practical study.

Define context is important, since some documents present case studies, there are documents of computer science data analytics and others related to the BDA process and theories. If, in the analyzed documents, is a case study it is considered a hypothetical or practical document, we continue to validate as an operations strategy and performance indicators matrix. So on, we validate the concept of the document, which are the resources, in this step we define resources used at the case studies which are the data analytics resources (e.g. tools and techniques of data analytics), also process resources (e.g. tools and techniques to process architecture) considering each step. Finally, considering operations management strategy and performance indicator we validate the process, in that we define participants (e.g. individual or group study), project management (e.g. if the participants are from managing, supporting or operational group), also we define the point of entry of the study, which is define expectations, understanding and agreement of the managing group.

After the literature review using operation strategy and performance indicators matrix, we define that some documents do not refer to data analytics process architecture. Thereby, we decide to exclude documents with specific contents in the area of computer science which relevance is related to the technical implementation of data analytics. As well, articles that cover areas correlated with the BDA, but that do not present it as the main area of process architecture, or even a fundamental step for the data process analysis. Considering this analysis, we came out with 23 documents, which are separated in four main areas: Process Architecture BDA, Process Architecture and Data Analytics, Theories of BDA and Simulation, presented in Figure 2.



Fig 2. Distribution of 23 papers main areas.

3 Results of the Systematic Literature Review on Big Data Analytics Process Architecture

Performing the literature review analysis we could verify that a construction of the data analytics process architecture could be represented in several areas. To develop a data analytics process architecture, it is important to understand the initial stage of data development, which could be represented by cyber-physical systems. According to Lee et al., it is important to define the connectivity to real-time data acquisition from the physical world, also the data analytics management that constructs the cyber-space. Another important point to understand when developing processes architecture in data analytics is smart manufacturing [7].

As presented by Tao et al. [8], industrial organizations use big data analytics to refine manufacturing process, the concept of data-driven smart manufacturing provides a full range of services to reduce losses and enable significant increases in manufacturing efficiency and improvements and product performance. In addition, simulation papers present the role of data analytics in manufacturing based on simulation context, using data analytics as direct use of simulation as data analytics application, or use the simulation for supporting data analytics applications [9].

Considering literature review present in many areas of application of data analytics in process architecture development, we define some recommendations to develop a framework of data analytics process architectures. Also, in the next section we will discuss each of its five layers.

3.1 Data Gathering

The first step that must be considered in the control of a BDA process architecture is related to data gathering, in that step is important to consider language, format and type of data. According to [10], it is important to create a multi-source heterogenous big data systems specifying which language will be used. The construction of an accurate cyber-physical systems enable data gathering to measure and control data indicators. Data gathering stage consider what is the type of data and how to select proper sensors. [7]

Data gathering depends on type and dimensions of data to develop data analytics process architecture. Data could be structured, semi-structured or unstructured. Dutta & Bose, present a case study with a variety of data gathered that could be separated in structured, which has a common language and interoperability (e.g. ERP database, charts) and unstructured data, that is represented by images, social media, text and other types of data (e.g. web site, excel sheets, streaming video) [11].

Hence, to develop and accurate data analysis it is important that process architecture consider the use of more than one type of data. Considering [12], the structured data is a relational database that has the same language, format and model of data. Semi-structured data could present some irregularities at the model. There is also unstructured data, which is raw and does not have a data model. It is a large number of data, without the same format or language. At construction of a reference architecture authors present

some extractions of each type of data using different tools to gather data as Scribe-Hadoop, MySQL and Kafka.

Considering [13], the authors presents a system architecture to implement intelligent predictive maintenance. In Data Gathering phase, data from several sources is collected and stored in MySQL database (e.g. operators and quality department). According to [9], is important to ensure that your data collection is generated according to principles of Big Data for analysis, there are four main manufacturing data characteristics: volume, veracity, variety and velocity. Considering these dimensions, authors propose the use of MTConnect Generation as a generation module to streaming the data and translate it into XML-based MTConnect.

3.2 Data Preparation

Data preparation is an important step to conduct transformation of raw data into usable and assertive data, considering that are many ways to transform data into information: using models, tests, statistics it depends on each project. This layer is the process between the gathering layers to process layer, it is the stage where you clean, standardize, validate and reformat the data to be able to analyze it [14].

According to [15], data preparation is an important stage of data transformation in big data analytics. To achieve that, there are some preprocessing operations to implement in datasets as noise reduction, outlier detection, anomalies removal, feature extraction, to create uniform datasets. In addition, [16] presented at CRISP-DM a reference model that considers the preparation level tasks as cleaning transform and model data. Another use of data for manufacturing analysis is presented by [17], the authors propose an architecture which is divided in extract, transform and load data and manufacturing process analysis. Then, they also propose extraction of process information with Mapper and Reducer of Hadoop framework and after that store the data.

After data preparation, cleaning, formatting and standardization it is possible to develop an effective data analytics. At this stage, it is important to define storages to collect and distribute data systems. As presented by [18] the preparation stage is important to preprocessing algorithms, some recommended tools to prepare data are Apache Pig to classify raw data and Apache Hive to generate basic tables from metadata.

3.3 Data Analytics

Considering the data was gathered and prepared, the next stage is to develop accurate information and efficient indicators.

According to [8] there is a variety of techniques of data modelling and analytics as clustering, machine learning, large scale computing. At this point, the efforts from data analytics engineer and the operator are very important to validate and develop a model with credible data and accomplish information with performance indicators. To implement a case study the authors use a variety of data to develop analytics using BR neural network, a smart failure diagnosis and cluster analysis. Also, considering data

analytics, quality information is important to develop dependable data models. To create a quality prediction model it is important to use some classifications algorithms as decisions tree, random forest and artificial neural network as analysis techniques, they used the R language to deploy the quality model, also used the RandomForest library to random forest and net library for artificial neural network. [19].
According to [20], the data collected need to have high dimensionality and large sample size to develop accurately indicators, these characteristics are important to analyze data in a more effective way. Big data analytics has a diversified range of research as simulation, maintenance, quality, and manufacturing. The use of analytics in predictive manufacturing is represented in the journal of [21]; use the predictive manufacturing to develop a model based on fuzzy unordered induction algorithm to predict performance of manufacturing. Data mining is one of the important steps of data analytics, according to [22] data mining need to consider two functionalities, first metric oriented root cause analysis which identify circumstances under which metric is selected. Second is the structure analysis that is based on clustering of selected process, thereunto authors presented some tools to data mining such as Java using WEKA.

According to [23], to develop manufacturing IoT is important to define the principle categories of data analytics, according to complexity and methods. The classifications of data analytics approaches are descriptive, diagnostic, predictive and prescriptive. Also, the authors develop a representative case study and use each category of data analytics. Another approach into big data analytics presented by [24] is complex atomic events, that are a mass of events that are a combination of methods, techniques and tools to analyze a mass of events in real-time to obtain accurate information to implement data analytics. Also Krumeich et al., introduce MapReduce that is a tool that decomposes a problem into independent subproblems that are distributed and solves by mappers.

3.4 Data Visualization

Defining a data visualization tool is an important task for the implementation of data analytics architecture, it provides information for operations strategy management that aims to decision making. There are a large number of ways of data visualization as a considerable numbers of charts, graphics, and tables and there are some specific platforms that are used for data visualization such as Tableau and PowerBi.

According to [18], there are plenty ways of data visualization that could be applied, in the case study the authors represented findings using charts and tables, also some examples of computer-aided engineering. Another tool to visualize graphical indicators is JFreeChart, use for root cause analysis or structure analysis; also there are WEKA for decision tree visualization [22]. Also, creating visual data is important to considerate the interface aspect since the user need to be well informed about data analyzed. According to [20], a data scientist needs to be careful on each tool or types of charts, which will be used to display the information.

Big Data systems need to be user-friendly and intuitive to provide a fast-response and enable users to search information. Another functionality of data visualization is for business intelligence, a user intuitive interface that has performance management,

operations strategy indicators and financial goals could improve decision-making. According to [12], there are solutions that offer intuitive visualization tools that consider user experience capabilities as Tableau, Karmasphere and Datameter.

3.5 Data Stakeholder

Considering the literature review developed at this paper, we propose. The data stakeholder stage. As presented in scientific study of Platts, the four main features characteristics of robust and successful methodologies for operations management, that are procedure, participation, project, management and point of entry. During literature review, we found a vast majority of papers presenting case studies of data analytics procedures and project management. As the aim of the paper is to provide a data analytics process architecture, reaching strategic operations to develop accurate indicators, we are considering also participation features and point of entry [2].

According to [2] the characteristics of project management methodology are adequate resourcing, agreed timescale and identify managing group, supporting group and operating group. In addition, participation methodology highlights individual and group commitments to support decision-making and develop workshops. To develop a data analytics architecture process framework we recommend to consider project management and participation aspects that will be present next. According to [25], data analytics uses model library to help the decision support. These decisions are targeted to different stakeholders and are available to continuous performance improvement as a component to dissemination.

Considering that premises, present at CRISP-DM [16] model business understanding as an initial phase that focus in understand project objectives and requirements from a business perspective, then converting this knowledge into a data mining problem definition and a preliminary plan designed to achieve the objectives. According to [24] is important to adapt and optimize business process. Also to create feedback channel from operations to business process execution to guarantee optimal business process. Develop a study based on interviewing manufacturing enterprises to define how the utilization of BDA changes manufacturing operations, and the results are that using BDA really enhances manufacturing performance, and such improvements can foster differential performance impacts on cost reductions, planning improvements, better prediction of events and enhance customer satisfaction. As a recommendation, the authors propose that enterprises should pay attention on BDA management capability, to create better utilizations of BDA in operations and process performance [1].

Develop a case study based on sustainability factors for manufacturing systems that present the importance of the participation of top management and executives to improve manufacturing organizational performance. Also, to enhance operational efficiency is important to integrate suppliers and customers. As one of the analysis presented management and leadership style the highest influence on BDA, also employees from all levels must participate in BDA adoption as a sustainable business performance [26].

Omar et. al [27] develop a framework considering the actors of business analytics ecosystems in manufacturing . As presented by Omar et. al [27]: 'Business units executives must recognize and solve problems based on evidence. This evidence is identified by personnel with analytical skills that apply statistical models to data. Also, business translator is responsible to bridge the work of analytical personnel to executives and managers. Top management sponsorship and buy-in is necessary to guarantee success. Finally, an IT team and external technology suppliers are necessary to provide the tools and processes needed for the aforementioned actors to generate value and deliver it to customers.'

Considering the literature review of operations management and BDA, we developed the data stakeholders stage. This is a data project management stage. When developing a data analytics project there are a range of enterprise areas involved. It is important to understand the business, but also your stakeholders. Developing an accurate and intuitive platform is important to guarantee better decision making, to do so, it is important to understand who will use the platform and how are the operations involved in the process that the platform will be applied. Understanding the context of the indicators (e.g. strategic indicator or operational indicator) is important to well inform your stakeholders. To do so, we propose that stakeholders participate in data analytics and data visualization stages as contributors to the development of indicators performance. The participation will be aimed at presenting insights and sharing knowledge about the process improvement and user experience through brainstorming and meetings. What we propose here is to create a multidisciplinary group with operational, supporting and management participants when necessary to develop data analytics indicators.

4 Proposed Big Data Analytics Process Architecture Framework

After literature review and discussion of the propositon of five stages, we propose a framework highlighting key aspects of big data analytics process presentend on Figure 3. To develop the framework we analyse all processes and architectures presented in the literature review and highlight similarities and differences. As presented in the literature review a majority of the documents present process architecture BDA recommendations, since gathering data to data visualization. According to [28], process and planning are the most prominent contributions of BDA, over 60% of the documents are architecture, platforms and frameworks.

Data Gathering is represented by CPS networks, it considers all the data providers in manufacturing site (e.g. sensors, RFID, ERP, excel sheets) at the end of this process we propose the use of a data storage based on literature review recommendations. At Data Preparion layer, as presentend in literature review an important step is to conduct transformation of raw data into usable and assertive data, we propose a process of gathering raw data, using a BDA tool presented on literature review, to transform, standardize and validate the data. In this step is important to mitigate data outliers, noise and anomalies.

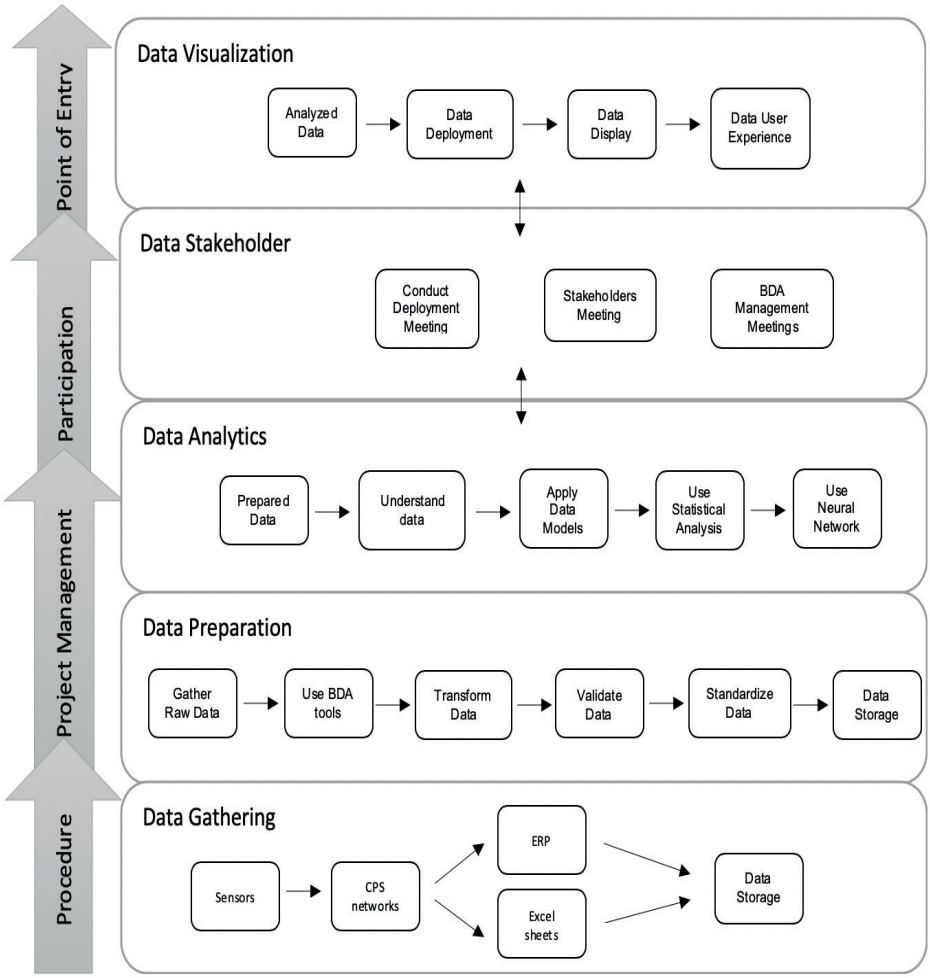

Fig. 3. Framework for Big Data Analytics Process Architecture.

Third layer is Data Analytics, it is important to develop the accurate information to develop accurate and efficient performance indicators to achieve organization's goals. At this stage, the data prepared will be transformed in information. To do so, it is important to understand data business, and to achieve that a data analytics group of study must understand which are the enterprise problems, goals and what they expect with the analysis. At this point we recommend a weekly meeting to allying stakeholders expectations with data analytics. It is important to highlight that, sometimes the data is not enough to develop better information, but when data analytics group meet with stakeholders, they could construct the paths to analyze data and achieve good performance indicators. After that, the data analytics group could apply the models of neural network, statistical models or other analyzes, it depends on what information

stakeholders need. At the end the group will conduct a deployment meeting with people involved on data transformation.

The fourth layer, Data visualization, according to our literature review this layer provides information for operations management strategy that aims to decision making. At this stage the data analyzed is displayed in performance indicators and informations in tables, charts and data visualization tools. At this layer it is important to guarantee that the data analyzed will present accurate business information. Also, it is important to guarantee good user experience, once the data will be used for different organization areas (e.g strategic, operational, support). To achieve that, stakeholders meetings will be required to develop indicators, after that information could be deployed.

The Data Stakeholder layer is represented without a prescriptive process considering. Considering [26], that presents factors for sustainable manufacturing BDA, one of the factors are management and leadership style which consider that all employees must participate to decide mission and vision of BDA adoption for sustainable business performance. Also, Data Stakeholder has interface process with data analysis and visualization, considering the importance of stakeholders from different management areas. It is important to understand the business, but also your stakeholders. Developing an accurate and intuitive platform is important to guarantee better decision making, to do so, it is important to understand who will use the platform and how are the operations involved in the process that the platform will be applied. The representation considers that stakeholders will participate during the process development of the two stages, presenting insights and requirements.

5 Conclusion

The paper presents recommendations for the development of Big Data Analytics Process Architecture according to literature review. The literature review is conducted using Proknow-C steps, in order to have a better portfolio of scientific documents, considering academic relevance for the study. Thereby, with the study, it is possible to notice that are authors which develop big data analytics process architectures for implementation and there are some recommendations of tools and techiniques. During the developmnet of the paper we noticed that architectures recommended by the selected authors, presented in the literature review, are not prescriptive to a generic situation, considering most being from case studies.

In this paper we present recommendations for implementing a BDA process architecture, considering what exists in scientific literature and some interesting points to be considered to develop a big data analytics process architecture. We recomend fives stages that are important to implement a data analytics project: data gathering, data preparation, data analytics, data visualization and data stakeholder. To define those stages we use documents with scientific recognition. After the literature review and recommendations we present a framework considering main processes and tasks to develop a big data analytics process architecture. For future research it would be interesting to carry out a practical application of the process to see if it will work in

different types of processes, since, as presented in the literature review, the process architecture could vary according to the case study.

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Melhores práticas em eficiência energética em edifícios comerciais: uma discussão sobre modelos existentes

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Abstract. A preocupação das organizações em redução de custos com energia elétrica, seja para otimização da economia organizacional, cumprimento de requisitos regulatórios ou melhoria da imagem no mercado, estão cada vez mais percebidos e incorporados no mercado corporativo. Assim, o objetivo deste artigo é discutir modelos existentes sobre melhores práticas em eficiência energética em edifícios comerciais. Para atingir o objetivo, foi realizada uma revisão sistemática da literatura em dezesseis artigos relacionados à temática, buscando suas principais contribuições e pontos convergentes. A pesquisa apresenta um panorama das proposições existentes de Modelos de Melhores Práticas de Eficiência Energética em edificações e principais contribuições, e pode ser utilizado como referência para proposição de novos modelos, considerando os *gaps* identificados neste estudo.

Keywords: Modelos, Shoppings Centers, Melhores Práticas em Eficiência Energética

1 Introdução

Na realidade do mundo contemporâneo, muitas das atividades desenvolvidas dependem do uso da energia elétrica. O uso deste insumo representa um fator essencial ao desenvolvimento de produção, melhoria da qualidade de vida, e no progresso de um país. Desta forma, a geração de energia elétrica é tratada como um ponto vital no debate estratégico, político e econômico dos governantes. Assim, buscando melhores formas de processos, formas de produção e utilização energética com melhores técnicas e ferramentas, que visam otimização de custos, vêm à tona a eficiência energética.

A preocupação das organizações em redução de custos com energia elétrica, seja para melhoria da economia organizacional, cumprimento de requisitos regulatórios ou

melhoria da imagem no mercado, estão cada vez mais percebidos e incorporados no mercado corporativo. Neste contexto, surge a necessidade de se analisar como estão as práticas em eficiência energética. Assim, a questão de pesquisa do presente artigo é: Qual o estado da arte em relação a proposição de modelos de melhores práticas em eficiência energética em edifícios comerciais? Considerando o grande consumo energético que os edifícios comerciais representam, delimitou-se, para esta pesquisa, analisar apenas o contexto dos edifícios comerciais.

2 Metodologia

Os métodos de coleta de dados compreenderam o estudo e análise de artigos científicos encontrados nas principais bases de dados, as quais *Scopus* e *Web of Science*. A justificativa da escolha dessas duas bases se dá pela relevância que as mesmas possuem no âmbito da pesquisa acadêmica. Para isso realizou-se uma revisão sistemática da literatura nas duas bases, sem limite temporal, com o padrão: TS para a pesquisa na *Web of Science* e *Tittle* - ABS - *Key* para pesquisa na *Scopus*, chegando em um total de 271 artigos que foram submetidos em processo de primeira filtragem, por meio de leitura prévia dos títulos para verificar alinhamento com o tema da pesquisa. Para finalizar o processo de filtragem, com o segundo filtro, os artigos foram submetidos à leitura integral para confirmar o alinhamento ao tema da pesquisa, e finalmente compor o Portfólio Bibliográfico (PB). Assim, chegou-se em 16 documentos, que fazem parte do portfólio bibliográfico final utilizado para esta pesquisa.

3 Resultados e discussões

Dentre a análise dos 16 artigos relacionados na proposta metodológica, o estudo inicia-se com a apresentação do *benchmark* de Chung, Hui e Lam (2006) onde os autores analisam esse método, como importante ferramenta para promover o uso eficiente de energia elétrica em edifícios comerciais.

Em outro estudo (JUAIDI *et al*., 2016) os autores apontam como estratégia de eficiência energética a automação dos sistemas de iluminação conforme demanda e tempo, ocupação de ventiladores com controle de utilização, emprego de cronogramas de manutenção. Também, Li e Li (2018) apresentam dentro dos processos de *benchmarking,* a validação de análise dos dados do desempenho energético, sobre o foco de identificação do potencial da economia de energia.

A utilização de lâmpadas de LED também foi analisada em outros estudos Toleikytè, e Bointner (2016), como proposta de melhor iluminação para os seus usuários e colaboradores. Neste estudo considera-se que a eficiência energética de *shoppings centers* deve estar embasada na estruturação políticas e planejamentos de metas que visam a economia na energia elétrica. Sobre o debate de estratégias de redução da demanda de energia elétrica, Raimondi et al. (2018), consideram o emprego de sistema de automação predial, para a maximização de economia de energia pela utilização de sensores que modulam o fluxo luminoso e o emprego de uso de claraboia, incentivando o uso da luz natural. A tratativa sobre a recursos naturais, percebida por Fitzge-

rald E Woods (2007), está direcionada aos mecanismos mecânicos de ventilação natural, com o objetivo de melhorar o resfriamento da área de alta densidade de um shopping: a praça de alimentação.

Os Sistemas de Ventilação e Ar Condicionado - *Ventilation and Air Conditioning Systems* (HVAC) também foram tratados, onde Mondal e Bhattacharya (2014) questionam a centralização de controle principal de ventilação, consumindo dessa forma maior quantidade de energia, quando se considera um sistema de controle distribuído, pode-se perceber uma redução do consumo de energia. Essa sugestão, representou no estudo uma diminuição do consumo de energia, assim como a redução de utilização de recursos como o cobre, plástico e aço, necessários para a confecção das peças (REBOLLO et al., 2016). Outros pesquisadores indicam a utilização a ferramenta, *Building Management System* (BMS), apontando essa como uma assertiva de estratégias na gestão eficaz de energia elétrica (CANBAY, HEPBASLI, GOKCEN, 2004).

Duas abordagens um pouco diferentes foram percebidas nos apontamentos de Fu e Zhang (2012) retratam projetos futuros, não se preocupando apenas em designs tecnológicos e desenhos futurísticos. Também, estudos de Fasiuddin, Budaiwi e Abdou, (2009) sugerem estratégias de custo zero, que podem ser utilizados na redução do consumo de energia elétrica, tais como: controle do termostato, controle de uso noturno, cronograma programado de operações.

Ainda dentro das propostas verificadas para a redução do consumo de energia, Çağlar (2011) trata em seus estudos um comparativo sobre o isolamento térmico, relacionando um edifício sem isolamento em comparação a um que possui isolamento e que utiliza diferentes fontes térmicas. No debate sobre as considerações sobre eficiência energética, Wang et al. (2006), apresentam uma metodologia de um diagnóstico que objetiva a identificação do baixo desempenho energético, assim como a verificação de suas causas.

Com base na concepção do design da construção, Aste e Del Pero (2013) debatem que as estratégias para melhorar a eficiência energética devem estar incorporadas não somente no planejamento de novas estruturas, novos edifícios; mas devem fazer parte na reutilização de estruturas antigas. Entrando um pouco em indicadores de eficiência energética, Pan (2011) traz a utilização do software *Energy Plus*, onde os parâmetros podem ser calibrados e detalhados de acordo com a conveniência do local, visando a redução do consumo de energia. Antunes, Carreira e Silva (2014) os autores identificam uma lacuna entre o gerenciamento de eficiência energética e sua implementação prática, e como proposta sugerem um Modelo de Maturidade em Gerenciamento, com base na ISO 50001.

4 Conclusões

O presente estudo verificou os mais variados esforços que contribuem para o uso otimizado da energia. Percebe-se e crescente preocupação com o debate de eficiência energética, destacando-se medidas de adoção em construções, onde essas preocupações são incorporadas já na concepção do projeto, edificação e manutenção.

Neste contexto, considerando a questão de pesquisa apresentada, constatou-se que proposições de modelos de avaliação de melhores práticas em eficiência energética ainda são pouco explorados. Assim, surge uma lacuna de pesquisa, que pode propor mais modelos de avaliação.

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Análisis de eficiencia de los bancos nacionales de los países del Mercosur en entornos difusos

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Abstract. Las técnicas tradicionales de evaluación de eficiencia, DEA, asumen la hipótesis de que los valores de *inputs* y *outputs* son determinados con certeza. Sin embargo, en el mundo real, muchos procesos de producción involucran a menudo datos que son imprecisos, vagos o ambiguos. En estos casos, la imprecisión o vaguedad puede ser expresada como una función de pertenencia dentro del ámbito de la lógica difusa. Si bien se han desarrollado varios modelos DEA-Fuzzy (FDEA) para manejar la incertidumbre en *inputs* y *outputs*, las aplicaciones para medir eficiencia en bancos han sido escasas.
El objetivo de este trabajo es aplicar en forma comparativa el modelo DEA-CCR y el método FDEA propuesto por Guo y Tanaka, que surge como una extensión del modelo CCR clásico. Este método, proporciona una medida de eficiencia para cada unidad evaluada a partir de vectores de *inputs* y *outputs* difusos triangulares simétricos.
Se utilizan estos métodos para evaluar la eficiencia técnica de las principales entidades bancarias de capital público de los estados que son parte o asociados al MERCOSUR. El estudio se realiza sobre las entidades bancarias nacionales de 9 países del MERCOSUR, en actividad durante el año 2019.
Se puede concluir que el modelo FDEA utilizado es aplicable y proporciona una medida de la eficiencia de las entidades bancarias a diferentes niveles de posibilidad, consistente con la proporcionada por el método DEA clásico.

Keywords: DEA-Fuzzy – Eficiencia - Imprecisión

1 Introducción

La evaluación de la eficiencia surge como un instrumento de apoyo a la toma de decisiones en el ámbito público y empresarial. Un aspecto relevante a considerar en la toma de decisiones es la naturaleza de la información disponible. Aunque existen problemas donde los datos suelen estar definidos de forma precisa, hay otros en los que se trabaja en escenarios donde los datos son imprecisos, vagos o se identifican con términos lingüísticos.

El análisis del desempeño se ha convertido en una parte vital de las prácticas de administración en la industria bancaria. Sin embargo, aunque la literatura internacional reporta un gran número de estudios que se han llevado a cabo, la gran mayoría se ha realizado en países desarrollados, con poca o ninguna atención a las economías emergentes. Hay algunos estudios en Latinoamérica que sí se enfocaron en la medi-

ción de eficiencia, utilizando modelos no paramétricos, específicamente DEA, [1], [2], [3], y [4].

Entre las aplicaciones que utilizan modelos DEA para estimar la eficiencia en bancos, la mayoría de ellas asume que los *inputs* y *outputs* son conocidos con absoluta precisión. Sin embargo, en el mundo real, muchos procesos de producción involucran a menudo *inputs* y *outputs* que son muy difíciles de medir de una forma exacta.

A pesar de la existencia de diferentes tipos de enfoques difusos para manejar la vaguedad y la incertidumbre dentro del ámbito de los modelos DEA [5], el método de nivel α de [6] es uno de los más utilizados por la información que proporciona. Resolver este modelo en un nivel de α dado, produce una eficiencia de intervalo para la unidad de toma de decisiones (DMU) bajo evaluación.

El objetivo de este trabajo es evaluar la eficiencia técnica de las principales entidades bancarias de capital público de los estados que son parte o asociados al MERCOSUR., aplicando comparativamente un modelo DEA clásico y uno fuzzy (FDEA).

2 Mercosur

Las economías estables, con sistemas financieros sólidos y bien organizados y legislación clara y estable, tienden a ofrecer un ambiente más propicio para la generación de resultados positivos y pueden influir en la eficiencia con que utilizan sus recursos.

El Mercado Común del Sur (Mercosur) fue formalmente creado el 26 de marzo de 1991, con la firma del Tratado de Asunción por los gobiernos de Argentina, Brasil, Paraguay y Uruguay, con el objetivo de lograr una mayor integración de las economías de los países miembros y acelerar el proceso de desarrollo económico. La República Bolivariana de Venezuela, ingresó plenamente al Mercosur en 2012, aunque se encuentra suspendida en todos los derechos y obligaciones inherentes a su condición de Estado Parte, por el Protocolo de Ushuaia. El Estado Plurinacional de Bolivia, se encuentra en proceso de adhesión. Además, el Mercosur tiene como Estados Asociados a Chile, Colombia, Perú, Ecuador, Guyana y Surinam.

Se trabaja, con especial importancia, en aspectos relacionados al sistema financiero con el objetivo de armonizar las normas que rigen el funcionamiento de los sistemas financieros de los países para obtener un nivel adecuado de solidez y transparencia.

3 Modelos y Metodología

DEA es una metodología de programación matemática, desarrollada específicamente para medir la eficiencia de un conjunto de unidades homogéneas (DMUs). Calcula la eficiencia relativa de cada unidad, con respecto al conjunto de todas las unidades analizadas. En una primera instancia, se calcularán los índices de eficiencia de cada banco mediante la aplicación de un modelo DEA con retornos constantes de escala orientado a productos [7].

Uno de los enfoques para modelar la incertidumbre dentro del ámbito de DEA, comprende los métodos DEA fuzzy (FDEA), que parten del álgebra de los conjuntos

difusos [8] para tratar la borrosidad y vaguedad en circunstancias de incertidumbre. Los modelos FDEA que se encuentran en la literatura son usualmente clasificados de acuerdo a cuatro enfoques generales ([9], [10]): enfoque de la tolerancia, enfoque del nivel α, enfoque del ranking difuso, y enfoque de la posibilidad.

En el enfoque del ranking difuso, la idea principal es encontrar los puntajes de eficiencia difusa de cada DMU usando programas lineales difusos que requieren ordenar el conjunto difuso. Este enfoque fue inicialmente desarrollado por Guo y Tanaka, [6]. Ellos propusieron un modelo difuso CCR en el cual las restricciones difusas fueron convertidas en restricciones ciertas, a través de predefinir el nivel de posibilidad y utilizar la regla de comparación para números borrosos.

La eficiencia difusa de cada DMU bajo evaluación con *inputs* y *outputs* simétricos triangulares difusos se obtiene para cada nivel α de posibilidad como un número difusos triangular no-simétrico.

4 Análisis y Resultados

La evaluación de eficiencia se realizará sobre las Entidades bancarias de capital público más representativas de cada uno los estados que son parte o asociados al Mercosur. El estudio se realiza sobre entidades bancarias nacionales de 9 países del Mercosur, en actividad durante el año 2019, excluyendo los bancos de Venezuela, Guyana y Surinam de los que no se dispone de información homogénea.

A fin de realizar un estudio transversal (*cross-sectional*), los datos se obtienen de la información Contable e Informes económico financieros, que cada entidad publica periódicamente en sus respectivas páginas de internet.

Es importante destacar que, en este trabajo, se determina el *output* bancario utilizando el enfoque de activos, donde los bancos son considerados intermediarios financieros. Las variables a utilizar, se clasificarán en *inputs* y *outputs* utilizando el enfoque de intermediación, que tiene en cuenta el rol tradicional de las entidades financieras que transfieren activos financieros desde unidades superavitarias hacia unidades deficitarias. El enfoque de intermediación, siguiendo a [11], se ha utilizado con una selección restringida de variables. En cuanto al tipo de variables a utilizar, serán en su mayoría variables de flujo, que se seleccionarán del Estado de resultados de los Estados Contables de las entidades.

En cuanto a las variables a utilizar en el proceso de trasformación de *inputs* en *outputs* se considerarán: como *inputs*, Depósitos y Gastos de operación, como representación de los fondos tomados (capacidad prestable), y de las remuneraciones de empleados y gastos necesarios para el funcionamiento del banco. Como *outputs*, Ingresos financieros e Ingresos por servicios, que reflejan los resultados obtenidos por el banco de su actividad financiera y de intermediación.

De la aplicación del modelo clásico con retornos constantes a escala (CCR) *output*-orientado, se obtuvieron 5 unidades eficientes y 4 ineficientes: Banco República Oriental del Uruguay, Banco Estado de Chile, Banco Agrario de Colombia y Banco Unión Bolivia. De la aplicación del modelo FDEA *output*-orientado, se obtuvieron resultados de eficiencias coincidentes, pero con valores de eficiencia difusos a través

de números triangulares. Estos resultados difusos permiten identificar, a diferentes niveles de posibilidad, los intervalos difusos de la eficiencia determinada con el modelo DEA clásico.

5 Conclusiones

En este trabajo se propone la utilización de dos modelos DEA, uno clásico y otro difuso, para evaluar las eficiencias de las entidades bancarias de países del Mercosur. En el caso del FDEA se utilizaron datos de *inputs* y *outputs* difusos. Las eficiencias obtenidas son números borrosos que reflejan la incertidumbre o vaguedad inherente a los problemas evaluados. Se puede concluir que el modelo DEA difuso utilizado, extiende el modelo clásico CCR a formas más generales donde se pueden incorporar datos nítidos, difusos e híbridos. Proporciona, además, información sobre la incertidumbre asociada a la eficiencia calculada, ya que permite identificar intervalos difusos, a diferentes niveles de posibilidad, de la eficiencia determinada con el modelo DEA clásico. Debido a que siempre existe incertidumbre en la información disponible, los modelos difusos de DEA pueden desempeñar un papel importante para los problemas de evaluación que existen de manera integral en el mundo real.

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Evaluación de la Eficiencia Técnica de los Centros de Atención Primaria Salud en la Ciudad de Bahía Blanca

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Resumen: El análisis de la eficiencia de una red de Centros de Atención Primaria de Salud (CAPS) adquiere relevancia debido a que los servicios provistos en este nivel de atención son financiados mediante fondos públicos. Existen diversos métodos de medición de la eficiencia de una unidad de producción que permiten evaluar su desempeño y proponer estrategias de mejora. En particular, para las instituciones proveedoras de servicios de salud existe una vasta literatura que utiliza el análisis envolvente de datos (DEA). En este trabajo se aplica el DEA para evaluar la eficiencia técnica de los CAPS del partido de Bahía Blanca (provincia de Buenos Aires, Argentina). Para ello, se agrupan los CAPS según las especialidades disponibles (enfermería, clínica médica y pediatría) y se emplea: un modelo DEA BCC *output* orientado y un modelo de Supereficiencia para evaluar la eficiencia técnica en cada grupo. Los resultados difieren entre los grupos. En los que tienen las 3 especialidades, la mayoría de los CAPS son eficientes. Por el contrario, en los CAPS que tienen enfermería y clínica médica, así como los que solo tienen enfermería, la mayoría de los CAPS son considerados ineficientes. Se concluye que puede aumentarse la eficiencia, a partir de incrementar las consultas y/o reducir la cantidad de horas de trabajo, en el uso de los recursos públicos asignados al primer nivel de atención en el partido de Bahía Blanca lo cual permitiría mejorar las condiciones de acceso de la población más vulnerable a la atención de la salud.
Palabras claves: Eficiencia técnica, Centros de Atención Primaria de la salud, Bahía Blanca.

1 Introducción

El análisis de eficiencia técnica en las unidades de producción (tales como industrias, empresas o instituciones) permite determinar, dada una cantidad de insumos, la máxima producción posible, o bien dado un nivel de producción estimar la menor canti-

dad de insumos necesaria. Así, se puede establecer si una unidad de producción se encuentra operando eficientemente o por debajo de sus posibilidades de producción. De tal forma, a partir de la estimación de la eficiencia técnica de cada unidad de producción se puede comparar lo que efectivamente cada una produce con lo que podría estar produciendo dado el nivel de recursos utilizado con el fin de determinar posibles mejoras en su desempeño.

La eficiencia de una unidad de producción se puede medir con indicadores de eficiencia parcial que relacionan un solo producto con un solo insumo o con métodos que suponen la existencia de una función de producción mediante la cual se estima la cantidad máxima de producción dada una cantidad de insumos [1]. Esta frontera de producción, que permite estimar la eficiencia relativa de cada unidad de producción [2], se puede construir a partir de: i) métodos paramétricos, que requieren especificar una forma funcional para los datos, como por ejemplo el Análisis de Frontera Estocástica y ii) métodos no paramétricos, que no requieren dicha especificación, dentro de los que se encuentra el Análisis Envolvente de Datos (en adelante DEA).

La metodología DEA estima fronteras de producción eficientes que permiten comparar el nivel óptimo y el nivel observado en las unidades de producción buscando establecer una frontera virtual de eficiencia técnica y comparando cada unidad de decisión (en adelante, DMU) con esa frontera. La solución óptima se obtiene resolviendo un problema de programación lineal que consiste en maximizar la relación insumo-producto de cada una de las DMUs. Su principal ventaja es que, además de permitir la comparación entre diferentes insumos y productos de varias DMUs, permite efectuar optimizaciones individuales para su mejoramiento frente a un punto de referencia virtual calculado con base en la información del conjunto. Por tales motivos el DEA se ha convertido en una herramienta valiosa para los análisis comparativos de eficiencia, particularmente en el sector público [3].

En el caso particular de los servicios provistos en las instituciones del primer nivel de atención de salud, que corresponde al nivel del sistema de servicios de salud que provee bienes y servicios de salud de menor nivel de complejidad, durante la década del ´90 los trabajos destinados a estudiar la eficiencia han sido menos habituales y en general, se empleaban en países como Estados Unidos, Inglaterra y España. Sin embargo, en los últimos veinte años han aparecido trabajos que analizan la eficiencia de los centros de salud proveedores de estos servicios principalmente en países en vías de desarrollo [4-8]. La técnica empleada con mayor frecuencia para analizar la eficiencia de estas organizaciones es el DEA [9]. En particular en Argentina, esta técnica ha sido empleada para evaluar la eficiencia técnica de 295 instituciones del primer nivel de atención distribuidas en distintas regiones del país a partir de información del año 2011 [10].

En el partido de Bahía Blanca (Argentina) funcionan 56 centros de atención primaria de la salud (en adelante CAPS) que dependen de la Secretaría de Salud Municipal (en adelante SSM) y brindan servicios de salud de bajo nivel de complejidad principalmente a la población sin cobertura de salud, con excepción de la colocación de vacunas incluidas en el calendario nacional de vacunación. El funcionamiento de estas instituciones se financia con fondos públicos, principalmente del nivel municipal de gobierno, por lo cual adquiere relevancia realizar un análisis de la eficiencia técnica de los mismos.

En este contexto el objetivo de este trabajo consiste en realizar un análisis de eficiencia de los CAPS del partido de Bahía Blanca para identificar entre ellos, cuáles son las instituciones "relativamente eficientes" y las "relativamente ineficientes", en que se diferencian y qué medidas de gestión podrían implementarse para mejorar su desempeño.

2 Metodología

Se aplicó la metodología DEA, técnica no-paramétrica, determinística, que recurre a la programación matemática para estimar fronteras de eficiencia y evaluar la eficiencia de unidades de producción homogéneas entre sí (DMUs), en este caso los CAPS. Este método permite calcular la eficiencia relativa para cada una de las CAPS, comparando sus *inputs* y *outputs* respecto a todos los demás CAPS.

Por las características del problema se utilizó inicialmente un *modelo DEA BCC output* orientado [11] debido a que, frente a la falta de información sobre el producto final en estas instituciones se define un modelo empírico en el cual es deseable analizar la factibilidad de expandir los *outputs* para los *inputs* considerados [12]. El enfoque orientado a productos, también es el adoptado para el estudio de la eficiencia en otras organizaciones proveedoras de servicios en el sector público debido a que, si bien los *inputs* son los manejados por las DMUs, existen barreras que impiden reducir o incrementar sus niveles, por lo cual es apropiado utilizar esta orientación donde se busca maximizar la producción considerado como dado el nivel de insumos.

Posteriormente se aplicó el *modelo Supereficiente* [13] para analizar las características de las DMUs con mejor desempeño.

2.1 Modelo DEA BCC *output* orientado

El *modelo DEA BCC output* orientado busca la maximización de la producción, dado el nivel de *inputs*, teniendo en cuenta el supuesto de rendimientos variables a escala [14]. Se asumieron retornos variables a escala debido a que existe una amplia distancia entre los valores máximos y mínimos de los *inputs* y *outputs* [15]:

$$\text{Max}_{\varphi,\lambda,s^+ s^-} \quad z_0=\varphi+\varepsilon\left(Is^+ + Is^-\right) \qquad (1)$$

$$\lambda Y=\varphi y_0+s^+$$
$$\lambda X=x_0-s^-$$
$$\vec{1}\,\lambda=1$$

φ denota la puntuación de eficiencia
λ es el vector(nx1) de pesos o intensidades
Y matriz de *Outputs* de orden sxn
y_0 representa el vector *Output* de la unidad que está siendo evaluada
X es una matriz de *Inputs* de orden mxn
x_0 representa el vector *Inputs* de la unidad que está siendo evaluada

Is+ vector de holguras *Output*
Is- vector de holguras *Input*

Una unidad será calificada como técnicamente eficiente si y solo si φ*=1 y todas las holguras son nulas s*+=0, s*-=0. En caso contrario la unidad será calificada como ineficiente. La eficiencia técnica *Output* de la unidad evaluada será igual a 1/φ*.

Aquellos CAPS que sean eficientes se ubicarán sobre la frontera y tendrán un coeficiente de eficiencia igual a uno mientras que los CAPS ineficientes estarán por debajo de la frontera obtenida y tendrán coeficientes de eficiencia menores que uno.

2.2 Ranking de eficiencia

Generalmente el modelo anterior obtiene más de una DMU con φ*=1, esto es, varias unidades compartiendo el primer lugar. En particular, el supuesto de rendimientos variables a escala adoptado conduce a clasificar como eficientes a una alta proporción de la DMUs. En ciertos casos, resulta interesante obtener un ordenamiento total de las DMUs.

Para romper con estos empates, Andersen y Petersen [13] proponen una modificación al modelo clásico, excluyendo a la unidad evaluada de una de las restricciones. Esto permite que existan DMUs eficientes con valor mayor a uno. A este modelo se lo conoce con el nombre de *modelo Supereficiente*. En este trabajo se lo utilizará conjuntamente con el *modelo BCC* para analizar la eficiencia técnica de los CAPS de Bahía Blanca.

2.3 Selección de las variables del modelo

En primer lugar, dado que los CAPS pueden variar relativamente según el tipo de especialidades médicas y no médicas que producen, se armaron *clusters* de CAPS para poder aplicar el método DEA que requiere DMU homogéneas [16]. Los grupos se armaron considerando únicamente las tres especialidades básicas del primer nivel de atención (enfermería, medicina familiar o medicina clínica y pediatría). Las características de los grupos y su tamaño se detallan a continuación:

> *Cluster* 1: está integrado por 31 CAPS que producen al menos consultas de enfermería, medicina familiar o clínica médica y pediatría.
> *Cluster* 2: compuesto por 13 CAPS que producen al menos consultas de enfermería y medicina familiar o clínica médica pero no de pediatría.
> *Cluster* 3: agrupa a 5 CAPS que solo producen servicios de enfermería.

Se excluyó un CAPS de la localidad por no pertenecer a ninguno de los grupos definidos. Asimismo, no se consideraron en el análisis los CAPS de Cerri y Cabildo, dos localidades que conforman el partido de Bahía Blanca, porque tienen distintas características de funcionamiento.

En segundo lugar, se aplicaron los modelos DEA a los grupos definidos. Para determinar la cantidad de *inputs* y *output*s en cada caso se utilizó la siguiente ecuación [17]:

$$n° \textit{ inputs} + n° \textit{ outputs} \leq (n° \text{ DMU}/3) \quad (2)$$

En este análisis, los *inputs* se refieren a los insumos empleados por cada CAPS, mientras que los *outputs* son los productos ofrecidos por los mismos. Entre los insumos se consideraron, por un lado, las horas anuales ofrecidas por el personal de salud para el año 2018, desagregado en tres especialidades (Enfermería, Medicina familiar o Clínica Médica y Pediatría) y, por otro lado, el espacio físico de cada establecimiento medido en metros cuadrados. Por su parte, entre los productos/servicios prestados, se consideraron las consultas efectivamente realizadas en cada uno de los CAPS distinguiendo según la especialidad (Enfermería, Medicina familiar o Clínica Médica y Pediatría), también para el año 2018. Estas variables *inputs* y *outputs* variaron en los modelos según el grupo de CAPS estudiado (Tabla 1).

Tabla 1. Variables utilizadas para el análisis DEA

	Cluster 1
Variables *Input*	• *x1*: Cantidad de horas trabajadas de Enfermería (2018) • *x2*: Cantidad de horas trabajadas de Medicina familiar o Clínica Médica (2018) • *x3*: Cantidad de horas trabajadas de Pediatría (2018) • *x4*: Superficie de cada CAPS (m2)
Variables *Output*	• *y1*: Consultas anuales de Enfermería (2018) • *y2*: Consultas anuales de Medicina familiar o Clínica Médica (2018) • *y3*: Consultas anuales de Pediatría (2018)
	Cluster 2
Variables Input	• *x1*: Cantidad de horas trabajadas de Enfermería (2018) • *x2*: Cantidad de horas trabajadas de Medicina familiar o Clínica Médica (2018) • *x4*: Superficie de cada CAPS (m2)
Variables *Output*	• *y1*: Consultas anuales de Enfermería (2018) • *y2*: Consultas anuales de Medicina familiar o Clínica Médica (2018)
	Cluster 3
Variables *Input*	• *x1*: Cantidad de horas trabajadas de Enfermería (2018)
Variables *Output*	• *y1*: Consultas anuales de Enfermería (2018)

Fuente: elaboración propia

Para determinar las horas ofrecidas por cada profesional se utilizó información proveniente de informantes claves de la SSM mientras que la cantidad de consultas se obtuvo de los Informes de Producción provistos por el Departamento de Epidemiología y Calidad de la SSM.

Se utilizó el DEA Solver de Excel para las estimaciones dado que permite realizar el análisis hasta para 50 DMU [18].

Como paso previo a la aplicación de la metodología DEA se calcularon medidas descriptivas básicas (media, desvío estándar, máximo, mínimo) de las variables bajo

análisis en cada grupo de CAPS. Es importante aclarar que si bien el cálculo de indicadores de productividad parcial para cada DMU es sugerido como un indicador de consistencia entre las distintas metodologías disponibles para analizar eficiencia [19] solo fueron calculados para el *cluster* 3.

El método DEA generaliza la medida de la eficiencia para un único *output* e *input* de una DMU, medida por el cociente *output/ input* transformando los múltiples *outputs* e *inputs* para cada DMU en un único *output* e *input* virtual [12]. En este sentido, a diferencia de los indicadores de productividad parcial, el método DEA permite reflejar la eficiencia global de todos los *inputs* empleados [20].

3 Resultados

A continuación, se presentan las estadísticas descriptivas y los resultados de los dos modelos para cada uno de los *cluster*.

Para los CAPS con al menos Enfermería, Medicina familiar o Clínica médica y Pediatría (*cluster* 1) los resultados descriptivos se muestran en la Tabla 2.

Tabla 2. Estadística descriptiva *Cluster* 1

Variables	Media	Desvío	Mínimo	Máximo	DMUs a las que corresponde el Valor	
					Mínimo	Máximo
x1	2257,74	1136,64	1320	6600	7, 8, 10, 11, 12, 15, 20, 22, 24, 31	1
x2	904,65	739,68	176	3432	24	29
x3	905,97	642,38	176	2860	10,27,31	21
x4	128,15	148,36	31	870	31	21
y1	5217,10	3824,00	992	19462	10	1
y2	1164,16	1057,01	217	5668	7	29
y3	881,39	790,10	0	3055	3,5,22	21

Fuente: elaboración propia

En la Tabla 3 se presenta el resultado para el modelo BCC *Output* Orientado para el *Cluster* 1.

Tabla 3. Eficiencia BCC *Output* Orientado *Cluster* 1

DMU	Eficiencia (1/φ)	Orden	Referentes eficientes			
CAPS 1	1,00	1	CAPS 1			
CAPS 2	1,00	1	CAPS 2			
CAPS 3	0,85	25	CAPS 2	CAPS 20	CAPS 27	
CAPS 4	1,00	1	CAPS 4			
CAPS 5	0,72	27	CAPS 1	CAPS 14	CAPS 20	CAPS 29
CAPS 6	0,93	24	CAPS 1	CAPS 14	CAPS 20	CAPS 27	CAPS 30

CAPS 7	1,00	1	CAPS 7				
CAPS 8	1,00	1	CAPS 8				
CAPS 9	0,96	23	CAPS 16	CAPS 27	CAPS 29		
CAPS 10	1,00	1	CAPS 10				
CAPS 11	1,00	1	CAPS 11				
CAPS 12	1,00	1	CAPS 12				
CAPS 13	0,67	29	CAPS 16	CAPS 27			
CAPS 14	1,00	1	CAPS 14				
CAPS 15	1,00	1	CAPS 15				
CAPS 16	1,00	1	CAPS 16				
CAPS 17	0,48	30	CAPS 1	CAPS 14	CAPS 16	CAPS 27	
CAPS 18	0,46	31	CAPS 16	CAPS 27	CAPS 29	CAPS 30	
CAPS 19	1,00	1	CAPS 19				
CAPS 20	1,00	1	CAPS 20				
CAPS 21	1,00	1	CAPS 21				
CAPS 22	1,00	1	CAPS 22				
CAPS 23	0,69	28	CAPS 16	CAPS 20	CAPS 27	CAPS 30	
CAPS 24	1,00	1	CAPS 24				
CAPS 25	1,00	1	CAPS 25				
CAPS 26	0,99	22	CAPS 1	CAPS 14	CAPS 20	CAPS 27	CAPS 30
CAPS 27	1,00	1	CAPS 27				
CAPS 28	0,78	26	CAPS 16	CAPS 20	CAPS 27	CAPS 29	
CAPS 29	1,00	1	CAPS 29				
CAPS 30	1,00	1	CAPS 30				
CAPS 31	1,00	1	CAPS 31				

Fuente: elaboración propia

La mayoría de los CAPS (21) presentan eficiencia técnica pura output y, por lo tanto, determinan la frontera eficiente, bajo el supuesto de rendimientos variables. El resto de los CAPS (3,5,6,9,13,17,18,23,26,28) son calificados como ineficientes, ya que podrían aumentar el *output* con la misma cantidad de recursos; por ejemplo, los CAPS 17 y 18 tienen las puntuaciones de eficiencia técnica (*output)* más bajas de aproximadamente del 48% y el 46%, respectivamente.

Complementando lo anterior, en la Tabla 4 se presenta la mejora potencial (en %) que debería experimentar cada DMU ineficiente en sus *inputs* y *output* para situarse en la frontera y ser eficiente en el sentido de Pareto Koopmans; es decir, cuando no se puede reducir ningún insumo o aumentar ningún producto sin aumentar o reducir otro insumo o producto, respectivamente.

Tabla 4. Proyección de mejora (%) del *Cluster 1*

DMU	*inputs*				*outputs*		
	x1	x2	x3	x4	y1	y2	y3
CAPS 3	0,00%	-15,12%	-40,92%	0,00%	155,02%	17,15%	999,90%
CAPS 5	-51,57%	0,00%	0,00%	-2,24%	39,01%	39,01%	999,90%
CAPS 6	-15,17%	0,00%	-29,03%	0,00%	7,34%	7,34%	7,34%
CAPS 9	-10,40%	-0,11%	0,00%	0,00%	180,81%	38,05%	4,60%
CAPS 13	-22,00%	-7,45%	-0,22%	0,00%	87,16%	53,92%	48,28%
CAPS 17	0,00%	0,00%	0,00%	-35,23%	110,27%	149,11%	114,19%
CAPS 18	-19,88%	0,00%	0,00%	-19,01%	118,80%	171,32%	118,80%
CAPS 23	-31,79%	0,00%	-13,31%	0,00%	99,18%	45,66%	45,66%
CAPS 26	-5,51%	0,00%	0,00%	-8,07%	0,72%	0,72%	0,72%
CAPS 28	-27,28%	0,00%	-46,82%	0,00%	27,98%	27,98%	28,78%

Fuente: elaboración propia.

Se observa que algunos de los CAPS ineficientes para mejorar su eficiencia no solo deberían incrementar la cantidad de consultas en sus especialidades, sino que también deberían reducir la cantidad de horas que actualmente tienen disponibles de las distintas especialidades. Esto podría ser interpretado de la siguiente manera: las CAPS ineficientes podrían atender a una mayor cantidad de pacientes con sus recursos actuales e incluso algunas deberían reducir la cantidad de horas ofrecidas para consulta.

Hay algunas excepciones, el CAPS 26, debería aumentar muy poco la cantidad de consultas anuales sin modificar prácticamente las horas de recursos humanos para llegar a ser eficiente y el CAPS 17 debería aumentar las consultas, pero no debería reducir las horas de ningún recurso humano para llegar a ser eficiente.

Los valores de proyección de mejora porcentuales para las consultas de pediatría en los CAPS 3 y 5 se explican por la ausencia de producción de ese *output* durante para el periodo en las mencionadas DMU que, en términos absolutos, representan 681 y 1151 consultas, respectivamente.

Por otro lado, los resultados del modelo de superficiencia muestra el ranking completo de las DMUs. En la Tabla 5 se presenta una extracción del resultado del modelo con las puntuaciones obtenidas por los CAPS eficientes. Se destaca la performance de la DMU 31 que obtuvo un puntaje de eficiencia de 5,87. Este CAPS contó para el período analizado con 1320 horas de enfermería, 1100 horas Clínica/General, 176 horas de Pediatría y 78,46 metros cuadrados obteniendo como resultado 2.392 consultas de enfermería, 1931 consultas de Clínica/General y 233 consultas de pediatría.

Tabla 5. Supereficiencia- Orden *Cluster* 1

DMU	*Score*	DMU	*Score*
CAPS 31	5,87	CAPS 2	1,37
CAPS 16	2,76	CAPS 7	1,37
CAPS 29	2,30	CAPS 8	1,26
CAPS 11	1,95	CAPS 19	1,20
CAPS 15	1,83	CAPS 21	1,12
CAPS 4	1,54	CAPS 22	1,10
CAPS 1	1,49	CAPS 25	1,06
CAPS 14	1,49	CAPS 12	1,04
CAPS 30	1,48	CAPS 10	1,00
CAPS 20	1,44	CAPS 24	1,00
		CAPS 27	1,00

Fuente: elaboración propia

Para el clúster de los *CAPS con Enfermería y Medicina Familiar o Clínica Médica*, los resultados descriptivos se muestran en la Tabla 6.

Tabla 6. Estadística descriptiva *Cluster* 2

Variables	**Media**	**Desvío**	**Mínimo**	**Máximo**	**DMUs a las que corresponde el Valor** Mínimo	Máximo
x1	1976,00	907,60	528	3960	33	41
x2	1159,31	758,98	207	2948	34	41
x4	77,40	33,36	40	165	35	41
y1	3762,15	1672,37	1762	6762	44	33
y2	1888,54	602,50	763	2973	38	34

Fuente: elaboración propia

En la Tabla 7 se presenta el resultado para el modelo BCC *Output* Orientado para el *Cluster* 2.

Tabla 7. Eficiencia BCC *Output* Orientada *Cluster* 2

DMU	**Eficiencia (1/φ)**	**Orden**	**Referentes eficientes**	
CAPS 32	0,78	8	CAPS 33	CAPS 34

CAPS 33	1,00	1	CAPS 33		
CAPS 34	1,00	1	CAPS 34		
CAPS 35	1,00	1	CAPS 35		
CAPS 36	1,00	1	CAPS 36		
CAPS 37	0,75	10	CAPS 34		
CAPS 38	0,35	13	CAPS 33	CAPS 34	CAPS 35
CAPS 39	1,00	1	CAPS 39		
CAPS 40	0,68	12	CAPS 33		
CAPS 41	0,79	7	CAPS 34		
CAPS 42	0,69	11	CAPS 33	CAPS 34	CAPS 35
CAPS 43	0,76	9	CAPS 33	CAPS 34	
CAPS 44	1,00	1	CAPS 44		

Fuente: elaboración propia

De los 13 CAPS que lo componen 6 fueron calificados como eficientes y 7 operando con ineficiencia técnica, es decir, que podrían mejorar su performance. Tal es el caso del centro de salud 38 que obtuvo la peor eficiencia relativa (35%). A continuación, en la Tabla 8 se detalla los porcentajes de mejora que deberían alcanzar cada una de las estas CAPS ineficientes para llegar a serlo.

Tabla 8. Proyección de mejora (%) del *Cluster 2*

DMU	*inputs*			*output*	
	x1	x2	x4	y1	y2
CAPS 32	0,00%	-19,29%	-6,37%	93,41%	27,89%
CAPS 37	-26,36%	-88,80%	-42,22%	118,62%	33,14%
CAPS 38	-19,01%	-66,54%	0,00%	189,05%	189,05%
CAPS 40	-80,00%	-73,30%	-10,52%	46,59%	75,89%
CAPS 41	-59,09%	-92,98%	-56,20%	30,38%	26,94%
CAPS 42	-63,47%	-77,12%	0,00%	44,79%	44,79%
CAPS 43	0,00%	-71,26%	-6,99%	181,54%	31,40%

Fuente: elaboración propia

En este caso se observa que los 7 CAPS ineficientes podrían mejorar su desempeño incrementando los dos servicios producidos, así como también reduciendo la cantidad de insumos utilizados, con la excepción de los CAPS 32 y 43 que no deberían reducir la cantidad de horas de Enfermería.

A continuación, en la Tabla 9 se exhibe parte de los resultados del modelo supereficiente para los CAPS que trabajan con eficiencia técnica. En este se puede observar que la unidad sanitaria 36 se ubica primera entre los CAPS eficientes del *Cluster* 2, aunque no presenta amplias diferencias con las otras DMUs.

Tabla 9. Supereficiencia - Orden *Cluster* 2

DMU	*Score*	DMU	*Score*
CAPS 36	1,04	CAPS 34	1
CAPS 39	1,01	CAPS 35	1
CAPS 33	1	CAPS 44	1

Fuente: elaboración propia

Por último, para el *Cluster* 3, en la Tabla 9 se presentan las estadísticas descriptivas.

Tabla 9. Estadística descriptiva *Cluster* 3

Variables	**Media**	**Desvío**	**Mínimo**	**Máximo**	**DMUs a las que corresponde el Valor Mínimo**	**Máximo**
x1	1320,00	0	1320	1320	45,46,47,48,49	45,46,47,48,49
y1	7300,60	5317,92	1581	12948	49	48

Fuente: elaboración propia

En la tabla 10 se presentan los resultados del modelo BCC *Output* Orientado y la proyección de mejora (%) para las unidades ineficientes. Se obtuvieron valores de eficiencia menor a 1 para cuatro (4) de las cinco (5) DMUs. En particular, en este caso al considerar un único *input* y un único *output* los resultados de este modelo son idénticos a los que resultan del proceso de calcular indicadores de productividad parcial para cada CAPS y compararlos con el valor obtenido por la mejor DMU.

Tabla 10. Eficiencia BCC *Output* Orientada y Proyección de mejora (%). *Cluster* 3

DMU	**Eficiencia (1/φ)**	**Orden**	**Referente eficiente**	***Inputs*** **x1**	***Output*** **y1**
CAPS 45	0,71	3	CAPS 48	0,00%	40,86%
CAPS 46	0,85	2	CAPS 48	0,00%	17,25%
CAPS 47	0,13	4	CAPS 48	0,00%	644,57%
CAPS 48	1,00	1	CAPS 48	---	---
CAPS 49	0,12	5	CAPS 48	0,00%	718,98%

Se observa que todas las DMUs deben incrementar la cantidad de consultas de enfermería para aumentar su eficiencia técnica, pero ninguna debería reducir la cantidad de horas de personal utilizadas. Las DMUs 47 y 49 serían los CAPS que mayor aumento deberían tener en las consultas anuales de Enfermería dados los recursos que disponen (Tabla 10).

4 Consideraciones Finales

El análisis de la eficiencia por tipo de CAPS permitió calificar la eficiencia relativa según el perfil de atención de los mismos. Para los CAPS que por lo menos tienen *enfermería, medicina familiar o clínica médica y pediatría* se observó que la mayoría son eficientes. Los CAPS ineficientes de este grupo pueden incrementar las consultas de todas las especialidades y/o reducir las horas de trabajo de algunas especialidades para incrementar su eficiencia técnica. De los CAPS que por lo menos tienen *enfermería y medicina familiar o clínica médica* más de la mitad se consideraron ineficientes. En este caso, estos podrían mejorar su performance incrementando las consultas y/o reduciendo las horas de trabajo en la mayoría de los casos. Las horas de trabajo que no son necesarias en los CAPS ineficientes de estos grupos podrían ser reasignadas a actividades no asistenciales dentro del CAPS o bien a otros CAPS de la red de acuerdo a la necesidad de servicios. Finalmente, para los 5 CAPS que solo tienen *enfermería*, los resultados mostraron que solo 1 es eficiente. Los CAPS ineficientes deben incrementar la cantidad de prestaciones ofrecidas para alcanzar la eficiencia técnica. Adicionalmente el modelo supereficiente aplicado a los grupos de CAPS donde varias DMUs resultaron eficientes muestra que en el *Cluters 1* existen instituciones con un desempeño desatacado entre las 21 clasificadas como eficientes mientras que en el *Cluters 2* no existe amplia diferencia entre los *score* de eficiencia de las DMUs con eficiencia técnica.

Es importante destacar que la técnica empleada obtiene los valores de eficiencia de cada unidad de producción a partir de la comparación con las restantes. Las recomendaciones obtenidas en cualquier caso son tecnológicamente factibles de realizar al ser calculadas a partir de aquellas unidades que presentan mejores prácticas. En este sentido, es importante aclarar que el tamaño de espacio donde se brinda la atención, es un insumo que, a diferencia de las horas disponibles de personal de las distintas especialidades, no puede ser fácilmente modificado por las autoridades sanitarias, al menos en el corto plazo. Sin embargo, la proyección de mejora indicada por el modelo para este *input* podría interpretarse en el sentido de que un CAPS podría operar en un espacio de mayor o menor tamaño según el signo de la proyección de mejora y esta información podría ser empleada por las autoridades sanitarias para tomar decisiones relativas a la reasignación de actividades o servicios ofrecidos en los distintos CAPS de la red.

Este trabajo presenta limitaciones relacionadas con las variables empleadas para medir los *inputs* y los *outputs* que se explican por la dificultad para conseguir información sistematizada en el sistema de servicios de salud. La especificación de la función de producción empleada, cuando las variables utilizadas para medir los resultados del proceso de producción son las consultas, plantea el inconveniente de que no necesariamente todas las visitas son adecuadas. Para resolver el problema de la ineficiencia asociada a las consultas innecesarias se han propuesto otras medidas de resultados que podrían utilizarse en los modelos DEA.

Por tal motivo sería importante perfeccionar el trabajo considerando más *inputs* y *outputs* de los analizados, tales como vacunas aplicadas o actividades de promoción realizadas en el CAPS y de este modo obtener datos más precisos, que permita realizar un análisis de eficiencia integral, considerando todos los CAPS y refleje las acti-

vidades de prevención y promoción de salud que se realizan en los centros de salud en el primer nivel de atención y constituye uno de sus más relevantes *outputs*.

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A Proposal for an Interoperable Data Collection System for Production Control on CNC Machining Lines of a Healthcare Product

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Abstract. The healthcare product manufacturing industries are constantly changing, so they must find new ways to remain competitive in the market. With the concepts of Industry 4.0, they search for new methods to integrate and optimize manufacturing processes. Seeking to contribute with optimization of the production control in CNC machining lines of a healthcare product, this research develops a system of data extraction and representation using an interoperable approach, called System ADCS 4.0. By its use, it is possible to share data in a systematic and structured way, so the management environment can control the production line process, evaluating the quality and productivity indicators of the company in an automated way. It consists of an application that receives the data from the machine and translates it into a proper ontology, developed during this research. This way, the data will be treated according to semantic rules, by the application of an inference engine, generating knowledge, that will support professionals to take assertive decisions based on the data generated and displayed in a dashboard. Forms were created, using the BonitaSoft, to represent the results obtained from the application of the System ADCS 4.0, which consists in the representation of the indicators and the defects that occurred during the machining process. The developed system helps companies to increase the productive process by reducing cost, time and it also helps professionals in the decision-making process.

Keywords: Industry 4.0, Healthcare Product, Data Collecting, Semantic Interoperability, Machining.

1 Introduction

The healthcare product manufacturing industry is constantly challenged to seek new technologies to attend to the demands of the consumers, who expect more complex products with a higher level of customization [1]. In this way, industries must find new

ways to remain competitive in the market. Considering that the healthcare industry is tightly connected to the welfare and lives of people, the industry must perform a thorough and accurate analysis of its products. In this scenario, with the Industry 4.0, it is possible to integrate and flexible manufacturing processes, aiming for optimized production, with efficiency and quality to attend current demands [2][3][4].

To better attend market demands, companies must develop a technological infrastructure capable of supporting the high flow of data through different development teams and multiple data systems, requiring a well-defined structure between the different phases and areas of the development process, to ensure the correct exchange of data in the production process.

Through semantic interoperability, autonomous systems can communicate and share data through interconnectivity, ensuring that they are shared between different areas as well as their correct understanding.

Considering this scenario, this research aims to develop a system to optimize the production control in CNC machining lines of a healthcare product, processing the production performance data automatically, reducing the problems during the planning of the line, which could cause impacts on process costs, among others. In this context, the research main objective is to develop a method of knowledge representation that collects data and monitors productive performance in machining machines of a healthcare product, using an ontological and interoperable approach, seeking the improvement of the production control.

To illustrate the path taken to achieve this objective, the following topics will be discussed throughout this article: Materials and Methods – used as tools for the technical development of research; Related Works – it consists of the study of different works and authors to understand the main themes linked to the research; Approach – in this topic, it will be illustrated and described the system's operation model; Proof of Concept – throughout this topic, the system's operation model is applied in a healthcare segment, to verify the consistency of the proposed method; Results Discussion – after this application, the results obtained from it were discussed and evaluated; Conclusion – this topic is the final one to synthesize the results and the achievement of the objectives.

2 Materials and Methods

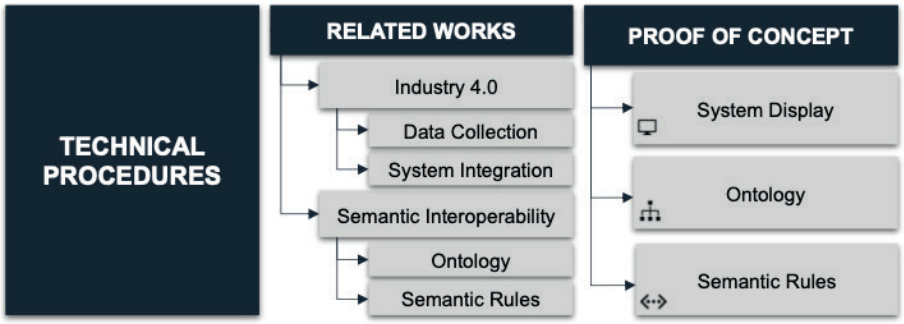
This research has an applied nature and an exploratory scientific objective because a problem situation will be mapped and explored to find a functional solution, by applying a pre-existing context. As the information analyzed is difficult to measure and seeks to analyze the quality of them, a qualitative approach was used. To achieve the objective of the research, the technical procedures (Fig. 1) were a literature review on works related to industry 4.0 and Semantic Interoperability, followed by a proof of concept, to evaluate the operation of the proposed method [5].

The following materials were used in the development of the research:

- Protégé – used for the creation of ontology, as well as for the application of an inference engine that consumes semantic rules, created in SWRL.
- Excel - used for creating and exporting semantic rules in SWRL language.

- BonitaSoft – used to describe the procedures performed by the ADCS 4.0 system, as well as to create the forms that represent the display of the results.

Fig. 1. Technical Procedures



3 Related Works

3.1 Industry 4.0

Industry 4.0 is understood as an integration between manufacturing processes, as well as information and communication technologies, especially the Internet-of-Things, which consists of real-world connection and communication, integrating intelligent systems into industrial processes [6][7]. Industry 4.0 emphasizes the e extension of a traditional manufacturing system to an integrated system, based on the connectivity of the platforms used in the industry, enabling the management of factories with complex and interconnected systems and machining processes, generating greater efficiencies in logistics operations [8][9][10].

The concept of Digital Manufacturing is linked to several advanced manufacturing techniques, such as Agile Manufacturing, MGrid, Rapid Prototyping, Additive Manufacturing, CNC, among others [11][12]. These concepts are also closely linked to Advanced Manufacturing, which seeks to assist in the constant increase of the efficiency of industrial processes, saving resources, and providing better products [13] These techniques are alternatives to traditional models, involving high-level technology and pioneering methodologies, which can deliver products and prototypes more quickly, involving multiple domains [14].

Through Industry 4.0, industries seek to achieve greater industrial performance by integrating processes and product connectivity [15]. Smart objects share information autonomously, such as their location, history, status, etc. This is due to the Internet of Things, which can connect all devices to an internet network. With the help of Big Data and Cloud-Computing, this information is collected, stored, and evaluated from various sources, supporting decision making, optimizing processes, saving energy, and. improving system performance [16]. By using the Internet of Things, it is possible to link the internet with the data collection system, making an integrated system, and with that, it is possible to handle and analyze a huge quantity of data without misunderstandings or loss of information [17].

3.2 Semantic Interoperability

Semantic interoperability is the communication capacity of autonomous systems through the use of common standards, allowing the sharing of data through interconnectivity, ensuring that the data shared between different areas has its meanings understood correctly throughout all phases of the product development process of a healthcare product. This is fundamental in the industrial processes since problems with data access and also the sharing of data from different sources and different systems can bring conflicts in the decision-making process [18][19][20][21].

By using an ontological approach, it is possible to describe and share data in a systematic and structured way, taking into consideration that ontology is an abstraction of a complex concept and, consequently, it is necessary to understand what one wishes to represent clearly so that there is no misunderstanding [22][23].

An ontological approach is a formal and explicit description of concepts, which are defined in classes, described by properties and attributes. This approach consists of classes, relationships, axioms, individuals, and functions. Classes represent a set of individuals with common properties, in addition, they are organized, usually in taxonomies, hierarchically through appropriate relationships. Relationships are associations between classes, in which their image determines a concept, through the representation of interactions between the elements of the classes. Axioms are always true conditions, in order to analyze the consistency of ontology. Individuals are entities that belong to classes that are used to represent specific elements, which are the data of ontology [23][24][25].

To ensure the sharing and veracity of data, ontologies in Web Ontology Language (OWL) can be used during the production development process of a healthcare product. Thus, to ensure the quality and productivity during this process, the relationships between the manufacturing data and the final product are translated into semantic rules, and to achieve this objective, it is used the Semantic Web Rules Language (SWRL) to represent that, by inferring new data, relationships, and it is also capable of producing results automatically by running an inference engine, that will translate the rules and extract knowledge from their results [26][27][28][29].

This inference engine infers knowledge in the ontology, from the application of semantic rules, this engine will cross the data, generating new knowledge from its predetermined conditions [30].

4 Approach of Automated Data Collection 4.0 System

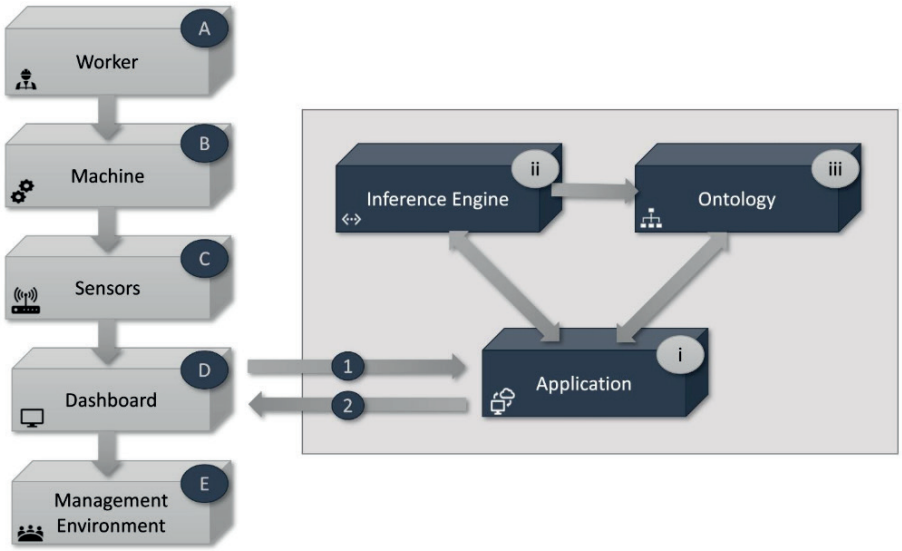
The research project was applied in a hospital production environment of the Institute of Bioengineering Erasto Gaertner (IBEG), located in Brazil in the city of Curitiba. IBEG is a national manufacturer of fully implantable Vascular Access Catheter indicated for people with long term treatment.

The company has a team of technicians specialized in machining, electropolishing, and assembly. The workpieces, which are the catheters, are produced through machining processes on Computer Numeric Control (CNC) machines. Nowadays, the data collection from the machining process is done manually by the workers, which may cause some troubles during the data documentation. The company constantly uses this data to make decisions that are very important for production control and the

evaluation of the indicators. Therefore, if the data is not accurate, the management environment can make wrong decisions that may harm the company and, especially, its customers.

Considering this scenario, this research seeks to improve the data collection process, by implementing a system able to support the company and the workers, through the automated data collection. Seeking to illustrate the process flow, it was possible to elaborate on an architecture that shows the system's operation, which represents all the stages of the production line (Fig. 2).

Fig. 2. Architecture of the Automated Data Collection 4.0 System.



Initially, an agent is required to perform his work (Detail A of Fig. 2). He is responsible to operate the CNC machine (Detail B of Fig. 2) and he must insert the system code on it to start the machining process. Then, the machine reads the code and starts to operate. After that, the sensors (Detail C of Fig. 2), installed inside the machine by a specialized company, will measure the machine data, like cycle time, cutting time, cutting speed, and vibration. Once the machining has ended, the workpiece that was machined will be measured manually and its data, as well as the machine data listed before, will be sent to a Dashboard (Detail D of Fig. 2), a virtual platform, where you can view the machine's performance indicators in an accessible way.

Connected to this dashboard, the system's application (Detail i of Fig. 2) will process the data to populate the ontology (Detail iii of Fig. 2). After populating the ontology, the application will apply the semantic rules through the inference engine (Detail ii of Fig. 2), in the ontology. This application, then, checks if there are any inconsistencies on the inference and until there is no inconsistency left, the application will correct them. But, if there is any inconsistency that cannot be automatically corrected, the dashboard must contact the responsible for the machine to correct the inconsistency manually. After the application of the inference engine on the ontology, the knowledge

generated will be sent back to the Dashboard (Detail D of Fig. 2), in which the management environment will analyze it and take necessary actions for the manufacturing process (Detail E of Fig. 2).

The dashboard shows the knowledge according to the parameters of quality and productivity through these indicators. At the end of the Automated Data Collection 4.0 System (ADCS 4.0) process flow, the dashboard organizes all the collected data in the machining process schematically, so that the Management Environment can make the necessary decisions, based on the data showed on the Dashboard.

5 Proof of Concept

5.1 System Display

The communication between the application and the dashboard, the application will process the information generated by the inference engine and the ontological base that will feed the platform of the dashboard from an outsourced company. The system, connected to an ontological database developed using the ontology editing software, Protégé, infers the data through a taxonomy created for ontology.

The dashboard will provide information to the system, forming a communication bridge between the software and the dashboard. The dashboard has an interface that presents the data to the company through graphs and tables according to the selected metrics and the KPIs.

The communication will be realized by importing and exporting files in .CSV (comma-separated-values), a format for storing information whit data separated by commas. The information will be exported by Excel software in a .CSV file template. The advantage over this file model is that it has a universal language and several applications can read, facilitating the import and export of data.

The data presented on the dashboard is generated from the collection made by sensors present in the machining machines. These sensors collect data as cycle time, cutting time, cutting speed, vibration, and preparation time. The data is sent to populate the ontology.

5.2 Ontology

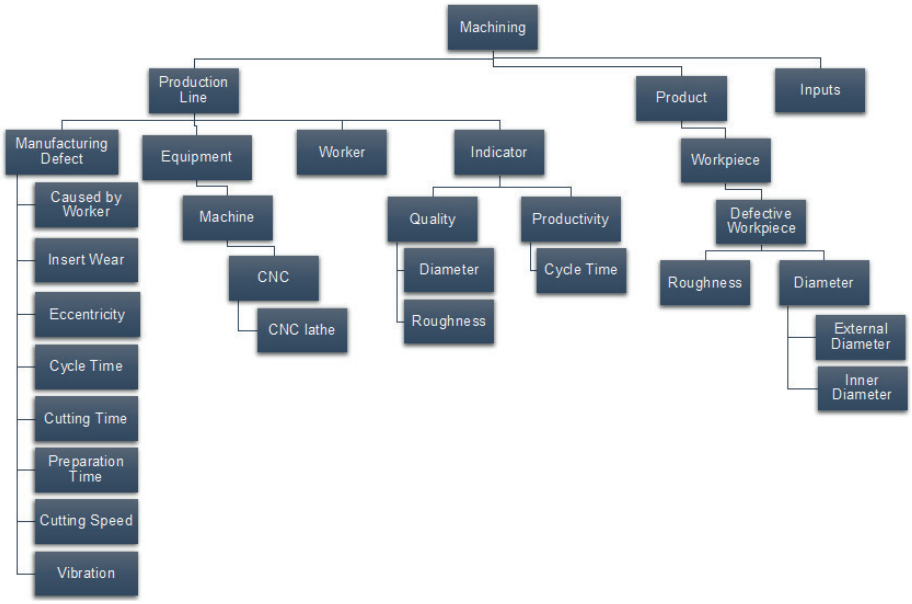
The construction of an ontology was one of the main focuses of this project, considering that by using an ontology, it is possible to represent a reality without misunderstands during the data sharing, by determining relationships between the data, to generate knowledge.

Aiming the ontology construction, it was necessary to determine a taxonomy that took into account all the steps involved in the machining process of healthcare workpieces in order to make the model as comprehensive and efficient as possible, from the machine and worker, till the application and dashboard.

Considering the proposed taxonomy model as shown in Fig. 3, the main classes are listed as production line, product, and inputs. Each blue rectangle represents a fragment of the taxonomy, whether a class or subclass. If a form cannot be unfolded, it is considered as an individual, else it is considered as a class or a subclass. The first subclass elaborated and analyzed within the production line class was the possible

defects that occur in a manufacturing process. Subsequently, the subclasses of the equipment class were included, which considers the equipment used for the machining process.

Fig. 3. Taxonomy of Machining.



The subclass "worker" was elaborated to control which worker was operating the machine in each shift of the production. In this way, it is possible to build a history of defects per shift so that improvements can be made assertively.

In addition to considering all the parties involved in the production process of the workpieces, the characteristics of the workpiece were considered, since these are the main factors that interfere in the quality indicators of the Biotechnology Institute of the Erasto Gaertner Hospital. Moreover, as the workpiece produced has a very important function for the health of the patients who use it, constantly controlling the number of defects found in the workpiece is essential. The characteristics that are most likely to suffer defects caused by a machining process, such as the external diameter, internal diameter, and roughness of the workpiece, were raised and selected.

Another indicator is taken into account in taxonomy and that needs attention and monitoring by the administrative environment is the productivity of the line in question. For this, it is necessary to evaluate the cycle time of the machining process, to ensure the demand of workpieces is met and that the company avoids waste or possible problems in the machine that may delay machining. Finally, resuming the importance of monitoring the characteristics of the machined hospital workpiece, the "Product" class was created separately from the production line, thus paying attention to the characteristics of the workpieces mentioned above. This ontology model receives assistance from semantic rules so that the inference engine infers on ontology, hierarchizing the information according to the model of the ADCS 4.0.

5.3 Semantic Rules

By creating the semantic rules, it is possible to determine a cause and effect relationship between the individuals, classes, data, and properties, to create knowledge that, in this scenario, will help professionals during the analysis of the production control, by showing them the quality and productivity indicators, and also the defects occurred during the machining process of the healthcare product.

For the creation of the semantic rules, it was necessary to understand what would be necessary to infer, to ensure the quality of the product and productivity, by identifying the parameters defined as ideal to create cause and effect relationships between individuals. Thus, it was necessary to conduct a research on the machining processes, verifying the parameters that can interfere in the final quality of the product, which has an acceptable maximum roughness of 1.6 mm, internal diameter of 12mm and external diameter of 20mm. In this way it is necessary to analyze the parameters that can negatively interfere with its machining, such as the insert wear, that can't be greater than 1.5mm, the cutting speed can't be greater than 110m/min. The vibration of the machine cannot be higher than 187 rpm. The eccentricity of the workpiece in the machine is also analyzed, and it must be close to zero to ensure the quality of the workpiece.

The cycle time is used to analyze the productivity indicator because if it is greater than 63 seconds, it means that problems occurred in the machining of the workpiece, which can be caused both by the operator, or by the preparation time, which can't be greater than 30 seconds, and the cutting time, not exceeding 33 seconds.

From the definition of cause and effect between the variables, it was possible to create semantic rules, using the SWRL (Semantic Web Rule Language), since this allows combining rules with ontologies developed in OWL, inferring new knowledge with the application of an inference engine.

The Fig. 4 shows a rule created, which this rule is interpreted as follow: if the machine "Y" has cycle time value "G", if "G" is greater than 63, the machine "Y" is operated by worker "H", the "Y" machine has a preparation time value "I", and if "I" is greater than 30, it is inferred that the "Y" machine has a defect of preparation time, and operator "H" causes the defect. All the preceding information of the symbol (à) is the body, and if this is true, what follows the symbol (head) will also be.

Fig. 4. Semantic Rule Example

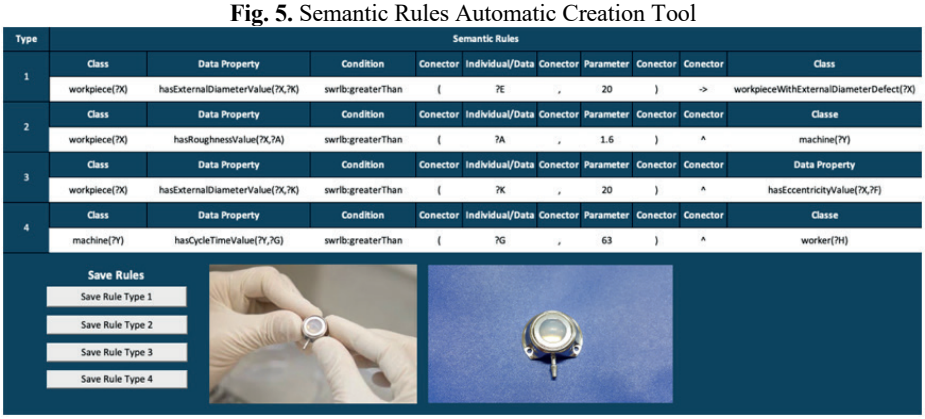
"machine(?Y) HasValueOf TimeCycle(?Y,?G) swrlb:greaterThan(?G,63) ^ worker(?H) OperatedByWorker(?Y,?H) ^ hasPreparationTimeValue(?Y,?I) swrlb:GreaterThan(?I,30) → DefectOfPreparationTime(?Y) DefectCausedByWorker(?H)"

To automate this process, a program was developed in spreadsheet software, capable of exporting the rules created so that the user can copy and paste them into the Protégé software on the ontology. First, it was necessary to create the rules, as previously presented, and with this, the elements used in their constructions were perceived, they are classes, object properties, data property, conditions, connectors, individuals/data, and parameters.

A spreadsheet was created in Excel with all these elements, mentioned above, one in each column, by filling them with the data of the ontology, enabling the creation of

a tool, using lists in the Excel software tool itself, allowing the selection of an element within each column, filling the respective cell. From this tool, presented in Fig. 5, and with the use of macros in Excel, it is possible to export each type of rule to a new worksheet, and from that, the user can copy the rule, in this new worksheet, and paste it into the Protégé software, inserting the semantic rule in the ontology, ensuring the functionality of the tool.

Fig. 5. Semantic Rules Automatic Creation Tool



Through this tool and with the application of an inference engine, new knowledge is generated, and its results are displayed in the Dashboard for the management environment of the company. For proof of concept, the results are displayed in a form by Bonita software.

These results are productivity indicators, analyzing cycle time, quality, analyzing the roughness and diameter of the workpiece, as well as resulting in the indication of defects occurred in the manufacturing process.

6 Results Discussion

During the development of this project the ADCS 4.0 was built, and it can collect data in an automatically and interoperable way for the production control in CNC machining lines. From a literature review, the concepts of Industry 4.0, interoperability, ontology, manufacturing, and machining processes, were studied and used to structure the project.

Through the system application, the machining process data are displayed to the management environment by forms created using the software "BonitaSoft". The forms show the data according to the KPIs in analysis about the machine and the manufacture of the pieces in a daily and weekly parameter, to assist the management environment through the analysis of the production control. The dashboard also shows the data inferred from the ontology, which are the quality and productivity indicators, such as the defects that occurred during the manufacturing.

The developed system brings qualitative benefits to the production. The collection and storage of data that was performed manually are now done digitally, which brings more precision in data collection and security in their storage. If this process is

performed manually, there may be the presence of human mistakes in the data collecting, and as they are stored on paper they can easily be lost, for example.

In addition to bringing more security to the productive control, automation also improves the quality and time of production. All records that needed to be done manually on paper by the operator, can now be done automatically, saving production time.

As shown in the Detail A of Fig. 6, the quality of the piece is measured by the values of the inner diameter, outer diameter, and roughness. The defects of the piece are measured with several parameters, as shown in the Detail B of Fig. 6: defects caused by the operator, defects caused by insert wear, defect in eccentricity, defect in the cycle and cutting time, defect in preparation time, and defect in vibration. These data are displayed together with the date and the time of production, the name of the operator, the piece number, and the machine number, and they are inferred by applying an inference engine through the semantic rules.

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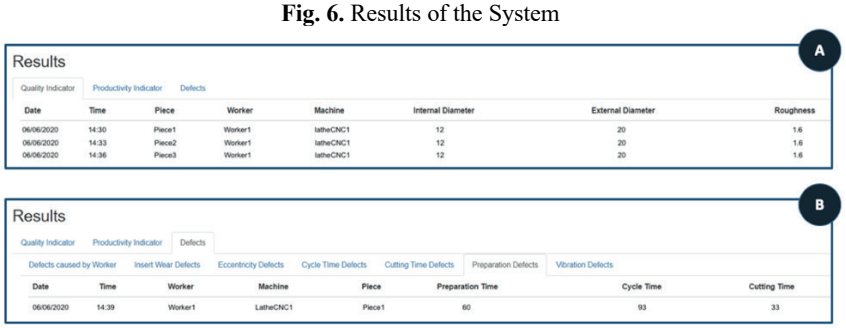
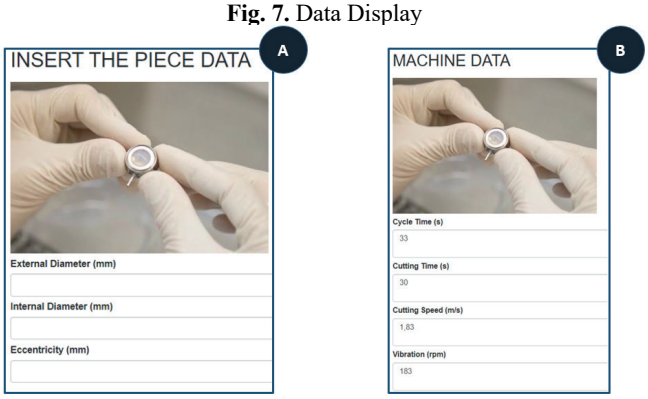
Fig. 6. Results of the System



The data displayed about the piece is internal diameter, external diameter, and eccentricity, shown in the Detail A of Fig. 7. The data presented about the machine cycle and cutting time, cutting speed, and vibration, as shown in the Detail B of Fig. 7. And the weekly data are insert wear, number of parts produced, and time of operation of the machine, the number of problems reported, and the roughness of the samples collected.

Fig. 7. Data Display



These indicators were selected for the production control because, after a field visit at the study company, it was confirmed that these were the most appropriate data for a good production control. Those data were already collected by the company, but the collection was realized manually by the operator and recorded on paper, which could generate many errors in the productive control.

The ADCS 4.0 contributes to the reduction of product development time because it automates the process of evaluating quality and productivity indicators. It also informs the management environment about the defects that interfere with these indicators, so that they can be solved as soon as possible, as well as contributes to the professional's decision-making process, without misunderstandings during the data sharing between all the stages of the manufacturing process.

7 Conclusion

A system was created for data collection, discarding the traditional and manual model. As shown earlier, it was possible to develop a virtual platform prototype for inserting and illustrating the data about the machine and pieces. In this way, it is possible to represent how the information would be displayed to the management environment, facilitating the visualization of the data, and supporting workers in the day-to-day work.

With this system, it is possible to perform a more efficient production control, monitoring all factors that can interfere with the company's indicators. With this, it is possible to raise the level of the organization generating financial gains, reducing processes time, and minimizing the defects, following the Lean Management and Industry 4.0 principles.

It was not possible to perform the data sensing in the machines, so the data used were approximated values, which can interfere with the conclusions about production if compared to the results obtained from real data on production. If the data were collected in a real application, the results can be significantly modified, influencing directly the company's assertive and agile decision making.

It is suggested, for further works, to apply this project using data from the machine sensors from a real production process, so that the results obtained could be more accurate, and also, it could help real companies to improve the production control.

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Máquina Paletizadora: Processo de Desenvolvimento do projeto

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Resumo. O objetivo deste estudo é descrever o desenvolvimento de uma máquina paletizadora para empresas que manufaturam produtos fracionados, dentre as quais inclui-se as alimentícias, calçadista, farmacêutica, automotiva, gráfica, eletroeletrônica, de materiais de construção, entre outras. Nesse contexto, observa-se problemas ocorridos pelo processo manual utilizado nas empresas, dentre os quais destacam-se as doenças relacionadas ao trabalho ocasionada pelos esforços e repetição das atividades. Desta forma, o desenvolvimento e aplicação do equipamento visa auxiliar a minimização ou eliminação das mesmas. Para isto, o referencial teórico adotado aborda os temas inovação, Processo de Desenvolvimento de Produto (PDP) e os tipos de carregamentos para o processo de paletização. Para atingir o objetivo, utilizou-se técnicas como por exemplo, a Matriz da casa da qualidade, Brainstorming e função global do produto e dividiu-se em tarefas dentro das fases de projeto informacional, conceitual e detalhado a partir do modelo de [15]. No estudo de caso, obteve-se as especificações-meta do produto no projeto informacional, na fase de projeto conceitual selecionou-se a concepção mais adequada e por fim, no projeto detalhado demonstrou-se o projeto com maiores detalhes. Utilizando essa metodologia desenvolveu-se o projeto de um equipamento novo no mercado, considerando uma alta produtividade, diminuindo os riscos com doenças relacionadas ao trabalho e respeitando as normas regulamentadoras de segurança.

Palavras chave: Inovação, Processo de desenvolvimento de produto, Paletização.

1 Introdução

Segundo [15], o Processo de Desenvolvimento de Produtos (PDP) visa desenvolver e atender a demanda de novos produtos no mercado, agregar novas tecnologias e adaptar a novos padrões. Isto é, através deste processo que as empresas criam novos equipamentos para satisfazer a necessidade dos clientes.

Assuntos como conforto e segurança, juntamente com características fisiológicas e psicológicas dos usuários possibilitam a criação de um relevante projeto [8].

Em virtude da globalização dos mercados, crescimento da variedade de produtos e a diminuição dos seus ciclos de vida, a aplicação de uma metodologia cientificamente embasada e suficientemente detalhada orienta o desenvolvimento de novas tecnologias auxiliando na inovação, ocupando-se desde a concepção e aplicação de novos produtos inovadores. Deste modo os novos procuram satisfazer segmentos específicos do mercado, associado a novas tecnologias e adequações a novos produtos e restrições legais [15].

Diante dessa realidade, a aplicação de uma metodologia científica no processo de desenvolvimento auxilia na inovação dos produtos, desde a concepção de ideia até a venda do mesmo, sendo isto um dos principais fatores no aumento da concorrência entre empresas.

As indústrias que manufaturam produtos fracionados, entre elas, alimentícia, calçadista, farmacêutica, automotiva, gráfica, eletroeletrônica, de materiais de construção, necessitam paletizar os produtos. A paletização dos produtos ocorre pela compactação, proteção, organização e praticidade da carga nos processos de armazenagem, expedição e transporte. Portanto, a paletização é um processo importante na manufatura de produtos, instigando as empresas a buscar soluções para diminuir ou cessar problemas ocorridos por doenças relativas ao processo manual e aumentar a produtividade.

Um estudo realizado pela Pesquisa Nacional da Saúde (PNS) em 2013, 3.568.095 (2,44%) da população tem diagnosticado problemas sobre Distúrbios Osteomusculares Relacionadas ao Trabalho (DORT), que são lesões ocasionadas por esforços repetitivos em decorrência do trabalho [1].

Estes sistemas automatizados economizam tempo e eliminam a necessidade de atividades pesadas de paletização manual no final da linha de embalagem, garantindo padronização, ergonomia aos colaboradores, segurança no processo e proteção ao produto final.

Neste contexto, o presente artigo tem como objetivo, descrever o desenvolvimento de uma máquina paletizadora para empresas que manufaturam produtos fracionados. Diante do contexto, pretende-se com o desenvolvimento do equipamento utilizando ferramentas do modelo de PDP, alcançar melhorias no processo de paletização com aumento da produtividade, diminuir tempo e custos com manutenção e minimizar ou cessar as doenças relacionadas ao trabalho causadas por esforços repetitivos.

2 Revisão Bibliográfica

Segundo [16], ao lançar um produto novo ao mercado entrega-se uma nova proposta de valor ao cliente, o que pode ser observado na forma de mínimas alterações. Além disso, a inovação pode ser percebida a partir de pequenas alterações, quase imperceptíveis aos usuários, até modificações que podem alterar a vida da sociedade [10].

Ao analisar a inovação em indústrias de fabricação de máquinas e equipamentos na Pesquisa de Inovação (PINTEC) em 2014, do Instituto Brasileiro de Geografia e Estatística (IBGE) cerca de 40% implementam inovação em produtos e/ou processos

(2657 empresas no total de 6588) e aproximadamente 33% implementam inovação organizacional e/ou em marketing (2191 empresa no total de 6588).

2.1 Processo de Desenvolvimento de Produto

Conforme [15], "Desenvolver produtos consiste em um conjunto de atividades por meio das quais busca-se chegar às especificações de projeto de um produto e de seu processo de produção". Além disso, o processo de desenvolvimento (PDP) pode ser definido como o conjunto de atividades que envolvem a maioria dos setores na empresa, tendo por finalidade modificar os requisitos do mercado em produtos ou serviços, que sejam economicamente acessíveis [5].

O PDP leva em conta os recursos tecnológicos disponíveis, a estratégia competitiva e de produto adotada pela empresa, abrangendo desde a captação das necessidades do cliente até o lançamento final e posteriormente retirada do mercado do antigo [2-15].

Para [2], as principais vantagens do desenvolvimento integrado são: redução do tempo de desenvolvimento, redução de modificações do projeto e aumento da qualidade sob diversos aspectos.

O modelo proposto por [15], conforme representado na (Fig. 1), unificou estudos de caso, modelos, metodologias e melhores práticas aperfeiçoadas ao longo dos anos anteriores. Este modelo baseia-se nos conceitos de Stage-gate.

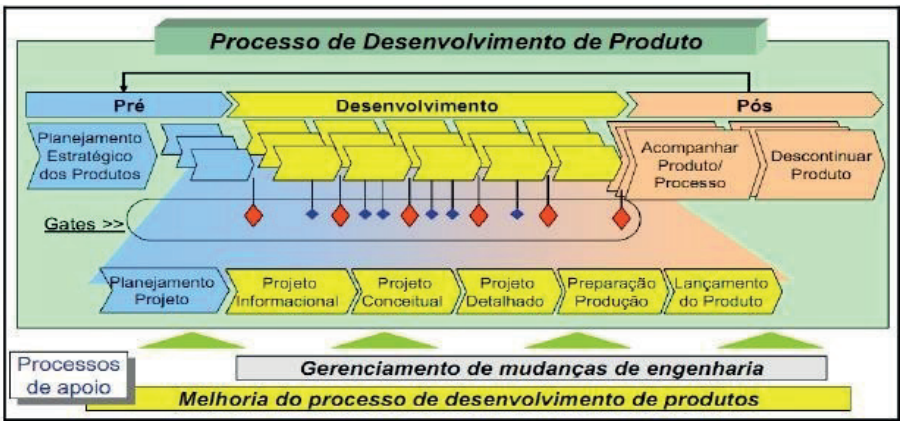

Fig. 1. Modelo unificado para o processo de desenvolvimento de produtos.

Para [12], as fases (Stages) são estipuladas pela entrega de diversos resultados. Quando agrupados geram um novo progresso para o desenvolvimento do produto. Enquanto os Gates são as transições de fases, os resultados obtidos são analisados, e verifica-se se o projeto deve continuar, além de corrigir diferenças de custos com o projeto inicial [14].

2.2 Processo de Paletização

Um paletizador é uma máquina que fornece um meio automático para empilhar caixas ou outras mercadorias e produtos em um palete para transporte e armazenamento eficientes. O ato de colocar caixas ou outros tipos de embalagem sobre paletes para manuseio, movimentação ou armazenamento pode ser feito manualmente por uma pessoa ou automaticamente por uma máquina paletizadora.

Para equipamentos mais automatizados há vários benefícios no carregamento de paletes como redução nos custos de mão de obra, aumentos na taxa de transferência, confiabilidade, reduções de tempo de inatividade, flexibilidade com os novos designs de paletizador atuais, segurança e ergonomia [13].

Para automatizar o processo de paletização deve-se decidir qual tecnologia utilizar. Tanto o carregamento formado por camadas quanto o carregamento robótico têm aplicações distintas. De acordo com a velocidade de camadas por minuto, utiliza-se um paletizador que se adequa melhor para a aplicação.

Conforme [6], o "Transporte manual de cargas designa todo transporte no qual o peso da carga é suportado inteiramente por um só trabalhador, compreendendo o levantamento e a deposição da carga". Portanto, a utilização contínua do corpo nesta função auxilia no desgaste de tendões, articulações e grupos musculares provocando lesões na coluna vertebral, tendinites, bursites e lesões musculares na região dorsal e lombar.

Há algumas soluções que podem ajudar no processo, como um encosto onde utiliza-se para guiar o processo de carregamento e que ajuda o trabalhador a gastar menos tempo alinhando o produto, além de um elevador com dispositivos de auxílio, como por exemplo atuador pneumático, facilitam o processo e são especialmente projetados para funções de paletização [13].

Ainda existem os processos semiautomáticos com máquinas ou robôs, possibilitando eliminar os riscos de lesões ergonômicas em trabalhadores e reduzir o erro do operador. O carregamento semiautomático adequa-se para altas velocidades que não justificam o custo de completa automação, mas requer uma solução para prevenir lesões de trabalho [13].

Ainda segundo o autor, as máquinas completamente automáticas são melhores ergonomicamente, pois possuem velocidade de paletização alta e são os mais eficientes tipos de equipamentos para paletizar. Porém, podem ser as mais caras, dependendo da velocidade da máquina, sofisticação de acumuladores, esteiras, distribuidor e outros mecanismos auxiliares. Outro processo automático, mas como o carregamento robótico, é utilizado e representa um alto investimento, mas o que pode salvar o custo inicial é a redução do custo de trabalho e aumento da eficiência, podendo construir vários paletes de várias linhas de produção.

São estabelecidos os principais tipos de paletização robóticos:

- Braços articulados: Nesta aplicação segura-se o produto recebido por um ou diversos braços articulados, e então posiciona-se no correto palete, considerando qualquer tipo de produto;
- Pórticos: O produto fica imóvel enquanto a ponte aérea move-se para frente e para trás pegando o produto e designando na localização correta.

Como exemplo de aplicação da paletização robótica, consideramos um problema de distribuição em uma produção industrial constituída por múltiplas linhas, utilizadas em centros de distribuição de produtos. Nesses casos, as caixas precisam ser empilhadas das correias transportadoras para os paletes com relação aos pedidos dos clientes. Sendo assim, as caixas atingem o paletizador no transportador principal de um sistema de coleta de pedidos, posteriormente um transportador de distribuição empurra as caixas para vários transportadores e finalmente, os braços robóticos posicionados no final destes destas linhas posicionam o produto em um palete localizado em um dos locais de empilhamento [11].

3 Metodologia

3.1 Modelo de Referência para o PDP

Entre os diversos modelos de PDP, escolhe-se para o estudo com maior detalhe o modelo unificado de [15], preferencialmente em virtude de maiores detalhes nas fases a serem desenvolvidas, com objetivo de descrever o desenvolvimento de um produto conhecido como máquina paletizadora para empresas que manufaturam produtos fracionados.

Ainda, empregou-se no desenvolvimento a ideia pertencente ao projeto de manufatura e montagem (DFMA – Design for Manufacture and Assembly). A utilização dos conceitos de DFMA tem por finalidade a diminuição de custos essenciais aos processos de manufatura e montagem do projeto. Por consequência, foram desenvolvidos elementos de simples fabricação e materiais com baixa mão-de-obra. Com o uso do DFMA, foi otimizado a aplicação de componentes normalizados no projeto.

Com o propósito de simplificar a compreensão sobre o modelo adotado, dividiu-se em fases (F), ferramentas (Fm) e tarefas (T) recomendadas para o desenvolvimento.

3.2 Ferramentas (Fm) do Projeto

As Fm utilizadas para a elaboração das tarefas das fases de planejamento do projeto, projeto informacional, projeto conceitual e projeto detalhado serão expostas a seguir:

Fm1 - Reunião com a equipe de projeto: Abre-se espaço para troca de informações com os demais integrantes da equipe. As reuniões tornam-se sempre sendo um divisor de águas para o sucesso do projeto [3].

Fm2 - Consulta a informações técnicas: Colher informações referentes à dados técnicos, imagens, vídeos e patentes de equipamentos paletizadores. Esta pesquisa pode ser feita por visitas técnicas, e-mails, acesso à web sites de empresas nacionais e internacionais, consulta a catálogos, acesso ao site do Instituto Nacional da Propriedade Industrial (INPI) e visitas as feiras de exposição.

Fm3 - Pesquisa com clientes: As pesquisas são divididas em qualitativas e quantitativas. Na qualitativa são identificadas as características do produto e na quantitativa realiza-se questões que ajudem com a pesquisa de informações para que se chegue aos objetivos de pesquisa [2].

Fm4 - Matriz da casa da qualidade: A matriz da casa da qualidade (QFD) faz a transformação da voz do cliente para a opinião técnica. A opinião do cliente descreve o que o produto necessita ter. As entradas para elaboração do QFD são feitas por entrevistas com possíveis clientes [2].

Fm5 – Brainstorming: Brainstorming é um método intuitivo de geração de soluções que consiste em um coordenador convidar um grupo de pessoas, sendo este grupo multidisciplinar, onde é exposto o problema. Os membros apresentam as alternativas que lhe vêm à cabeça, sendo evitado qualquer tipo de crítica sobre as soluções apresentadas.

Fm6 - Função global: Adquire-se a função global pela análise dos requisitos funcionais incluso na lista de especificações-meta do produto. A função vai sendo desdobrada em funções de menor complexidade. A elaboração da função total do produto ajuda a equipe de desenvolvimento a entender o que realmente se aguarda do produto projetado [15].

Fm7 - Matriz morfológica: Define-se inicialmente o problema, então são pesquisadas formas alternativas para resolução do problema. A matriz proporciona uma avaliação das prováveis configurações do produto. A combinação destes elementos serve de influência para novas ideias.

Fm8 - Matriz de decisão: Realizado a matriz morfológica, devem-se juntar os princípios de solução, respeitando a compatibilidade física e geométrica entre as soluções. São possíveis diversas combinações. A matriz sugere a utilização das especificações técnicas de projeto e os valores resultantes da QFD [15].

Fm9 - Consulta a padrões de cálculo: A equipe de desenvolvimento utiliza padrões de cálculos já consagrados de elementos de máquinas e manuais de fornecedores, que contém sistemas computacionais para ajuda nos cálculos [15].

Fm10 - Software 3D: A equipe de desenvolvimento pode modificar diversos parâmetros, como dimensões, tolerâncias e tipos de materiais e verificar instantaneamente os impactos ocorridos no projeto [15].

3.3 Projeto Informacional

Desenvolve-se nesta fase o conjunto de informações, denominado especificação-meta do produto. Essas especificações orientam a geração de soluções, orientam critérios para avaliação e de tomada de decisão utilizados nas etapas decorrentes do processo de desenvolvimento. Esse conjunto de informações deve refletir as características que o produto deverá ter para atender às necessidades dos clientes [15].

Para [2] o projeto informacional "destina-se à definição das especificações de projeto do produto. Nesta fase acontece a primeira reunião da equipe de desenvolvimento, para apresentação do plano de projeto" Uma vez iniciado, são realizadas seis tarefas (T) que buscam a definição dos fatores de influência no projeto do produto.

T1 – Pesquisar informações técnicas: tem por finalidade coletar informações que contribuam para a equipe de projeto a entender melhor o problema, sendo utilizadas as Fm1 e Fm2 [15].

T2 – Definir ciclo de vida do produto: auxilia o desenvolvimento do produto, mapeando ao longo do caminho os materiais, a fim de identificar as necessidades na origem, uso e descarte dos produtos, utilizando a Fm2.

T3 – Identificar os requisitos dos clientes: reconhece os desejos e necessidades dos clientes de máquinas paletizadoras, deixando essa linguagem mais apropriada ao desenvolvimento de produto. Para esta tarefa, utiliza-se a Fm3.

T4 – Definir os requisitos do produto: converte os requisitos dos clientes em requisitos do produto. Devem ser definidas as características de engenharia que menciona as funções e grandezas físicas referentes ao produto, realizada usando a Fm1 [3].

T5 - Hierarquizar os requisitos do projeto: organiza os requisitos de acordo com a equipe de projeto a fim de organizar em forma hierárquica. São utilizadas as Fm1 e Fm4 [3].

T6 – Determinar as especificações do projeto: nesta atividade procura-se especificar os requisitos de projeto, concedendo informações como valores e metas desejáveis, a maneira de avaliação e as características a serem evitadas na realização do requisito. Utiliza-se as Fm1 e Fm2 [3].

3.4 Projeto Conceitual

Segundo [2]: "Esta fase destina-se ao desenvolvimento da concepção do produto".

O projeto conceitual tem a função de fornecer convicções de projeto para o novo produto. Deve-se satisfazer a expectativa do cliente e distinguir o seu produto com relação aos concorrentes [4].

Ainda segundo o autor, os dois segredos do projeto conceitual são gerar o maior número de ideias possíveis e escolher a melhor de todas. Para [9], a geração de conceitos necessita muita criatividade, pois as invenções são feitas nesta fase. Para [2], o projeto requisita ter grande conhecimento nesta fase.

Conforme o projeto informacional, esta fase é dividida em quatro tarefas que orientam ao desenvolvimento da concepção do produto.

T7 – Definir a função global do produto: representa a relação entre as entradas e as saídas que especificam a função principal do produto. Esta tarefa auxilia a equipe de desenvolvimento a sintetizar o que se aguarda do produto projetado. Aplicam-se as Fm1 e Fm6 [15].

T8 – Definir as subfunções do produto: acontece a decomposição da função global em funções parciais, sendo elas em menor grau de complexidade. A estrutura é dividida até atingir um nível satisfatório de complexidade. Nesta tarefa emprega-se as etaps Fm1 e Fm6 [15].

T9 – Desenvolver princípios de solução: nesta tarefa são atribuídos diversos princípios de solução que atendam as especificações da estrutura funcional já definido na tarefa T8. A equipe de desenvolvimento deve criar várias soluções alternativas para o problema. Passa-se do abstrato ao concreto, da função a forma. Empregam- se as etapas Fm1, Fm5, Fm7 e Fm8 [15].

T10 – Desenvolver alternativas de solução e selecionar a mais adequada: desenvolver o maior número possível de princípios de solução para cada função, compara-se e combina-se soluções e então, seleciona-se por meio de análise comparativa a

mais inovadora concepção para o produto. Emprega-se as etapas Fm1, Fm5 e Fm9 [15].

3.5 Projeto Detalhado

O projeto detalhado tem como objetivo desenvolver e finalizar todas as especificações do produto para serem encaminhados à manufatura e às outras fases (F) do desenvolvimento [15].

Desenvolve-se nesta fase os sistemas, subsistemas e componentes (SSC). Aqui ocorre a documentação final e aspecto do produto. Simultaneamente são realizados o planejamento do processo de manufatura e os recursos do projeto [15]. A fase é dividida em duas tarefas que direcionam ao desenvolvimento as especificações do produto.

T11 – Dimensionar SSC`s: busca-se dimensionar os SSC`s da paletizadora através de equações, observadas principalmente em livros e catálogos. Este procedimento tem a função de estimar as dimensões do elemento verificado no projeto conceitual. Utiliza-se as Fm1 e Fm9 [15].

T12 – Projetar SSC`s: a partir de um dimensionamento inicial, há o início da elaboração dos SSC`s em um software de desenhos tridimensional (3D). Com ele é possível identificar prováveis interferências, maneiras de montagens, análise de movimentos, peso e resistência [7]. Esta tarefa utiliza-se as Fm1 e Fm10.

4 Desenvolvimento projeto máquina paletizadora de caixas

O sistema de carregamento definido para o estudo é o de alto nível, com o propósito de atender as necessidades de uma agroindústria do estado de Santa Catarina situado no Brasil. O material transportado são caixas de papelão de 15 kg com dimensões de 600 mm x 400 mm x 150 mm para comprimento, largura e altura, respectivamente. Para o tamanho do palete, será seguido a norma ABNT NBR 8252 – Dimensões básicas, de 1200 mm X 1000 mm X 145 mm para comprimento, largura e altura, respectivamente. Com o processo de paletização completo, o palete terá uma altura de 2200 mm e uma massa de 1200 kg.

Ainda, o projeto tem por intuito evitar problemas de saúde dos colaboradores no setor de paletização, seguindo normas regulamentadoras, como a NR12 e NR17 e aumentar a produtividade, tendo um ciclo do processo em média de 12 minutos.

Sendo assim, o desenvolvimento do projeto está dividido nas fases de projeto informacional, conceitual e detalhado conforme o modelo unificado PDP descreve.

4.1 Projeto Informacional

T1 - Pesquisar informações técnicas: Nesta tarefa buscou-se informações para auxiliar a equipe de desenvolvimento a entender o problema do projeto. Primeiramente, elaborou-se um banco de dados com imagens e vídeos de paletizadores de caixa disponibilizado no mercado nacional e internacional. Também, documentou-se as informações

através de buscas na internet, visitas em feiras e empresas. Com isto analisou-se os produtos concorrentes, processo de operação do produto e normas de segurança.

T2 – Definir ciclo de vida do produto: Auxiliou o processo de projeto a determinar o que foi realizado nas diversas operações de uma máquina paletizadora.

Durante este ciclo evidenciaram-se: projeto de produto, fabricação, montagem, operação e manutenção. Na fase de projeto de produto buscou-se desenvolver segundo exigência do cliente, sendo o equipamento altamente funcional e sem apresentar ameaça aos operadores e mantenedores. Na fabricação empregou-se materiais com baixo custo de aquisição e menor atividades dos processos de transformação. Na montagem, a padronização dos parafusos a fim de facilitar a fabricação. Para operação os objetivos no ciclo de vida são de não expor os operadores a risco de acidentes. Na operação de manutenção não expor o mantenedor a riscos de acidentes e facilitar a manutenção.

T3 – Identificar os requisitos dos clientes: Para saber quais são as principais necessidades dos clientes, aplicou-se um questionário em algumas empresas da região oeste de Santa Catarina. As questões tiveram o propósito de montar a casa da qualidade e averiguar os principais problemas enfrentados das empresas atualmente. Todas as empresas possuíam o sistema de paletização, com maior quantidade para o sistema manual. Os requisitos dos clientes estão ilustrados na tabela 1.

Tabela 1. Requisitos dos clientes

Requisitos dos clientes	Valores	Requisitos dos clientes	Valores
Simplicidade na operação	3	Robustez	4
Baixo custo de aquisição	3	Alto desempenho funcional	5
Qualidade do equipamento	4	Peças padronizadas	5
Segurança na operação	5	Baixo ruído	5
Dimensões (layout)	3	Utilizar o menor número possível de componentes	4
Durabilidade dos componentes	5	Fácil Instalação	3
Alta tecnologia	3	Fácil manutenção	4
Ergonômico	4	Dispensar mão-de-obra especializada	4
Design do equipamento	2	Minimizar impacto ambiental	4

Levando em consideração esses aspectos, observou-se que os entrevistados necessitam um equipamento seguro, funcional, de baixo ruído e com peças padronizadas, facilitando a montagem e manutenção.

Nas demais questões, observou-se com esta pesquisa que o principal problema enfrentado das empresas se trata de ergonomia. Verificou-se que os colaboradores exercem posturas inadequadas, com repetição excessiva dos movimentos na coluna vertebral, podendo provocar posteriormente lesões musculares, tendinites, bursites, além de expor-se ao risco de acidentes.

T4 - Definir os requisitos do produto: Nesta tarefa, buscou-se a tradução das necessidades dos clientes, resultante dos questionários, para uma linguagem mais técnica, como a da engenharia. Estes requisitos, conforme tabela 2, são expressões padronizadas possíveis de serem mensuráveis por algum tipo de sensor.

Tabela 2. Requisitos do produto

Requisitos do produto	Uni.	Requisitos do produto	Uni.
Forma construtiva		Frequência de manutenção	Qtd/ano
Componentes normatizados	Un.	Capacidade de produção	Kg
Custo do equipamento	R$	Nível de ruído	dB
Inovação tecnológica		Higienização	
Resistência dos materiais	Mpa	Peso	Kg
Número de peças	Qtd.	Tempo do processo	Min
Custo de manutenção	R$	Dimensões	mm
Custo de instalação	R$	Componentes recicláveis	Un.
Componentes simples	Un.	Potência consumida	kW

T5 - Hierarquizar os requisitos do projeto: Nesta tarefa tornou-se necessário ranquear os valores do cliente para cada requisito do produto, além de analisar o relacionamento existente entre os requisitos de projeto, sendo assim nesta tarefa foi utilizada Matriz da casa da qualidade.

Para classificar os requisitos do produto, atribui-se valores de 5, 3 e 1 para forte, médio e fraco relacionamento, respectivamente. Posteriormente, multiplicaram-se os relacionamentos com os requisitos do cliente já disponibilizado na T3.

Realizado a matriz da casa da qualidade, percebeu-se que a ordem decrescente dos requisitos com maior pontuação foi:

1. Componentes normatizados;
2. Forma construtiva;
3. Inovação tecnológica;
4. Custo do equipamento;
5. Resistência dos materiais;
6. Custo de manutenção;
7. Número de peças;
8. Custo de instalação;
9. Frequência de manutenção;
10. Componentes simples;
11. Nível de ruído;
12. Capacidade de produção;

4.2 Projeto Conceitual

T7 – Definir a função global do produto: Descreveu-se nesta fase a função que o produto executa e justificou-se a sua existência, caracterizando as entradas e saídas associadas ao processo de paletização.

A função global intitula-se como “paletizar caixas”. Determinou-se “caixas” pelo motivo de abranger diversos produtos e fácil manuseio. Com o fluxo de material, energia e sinal, pode-se empregar um diagrama de bloco e representar as conexões entre as entradas e saídas do sistema.

Desse modo, entram-se na função global a energia elétrica, materiais como caixas e paletes e o sinal de status da máquina. Na saída, espera-se alcançar energia elétrica, trabalho realizado, vibração e ruído, como material tem-se as caixas organizadas sobre o palete e sinal como status de deslocamento. Portanto, desenvolveu-se o esquema ilustrado na (Fig. 2).

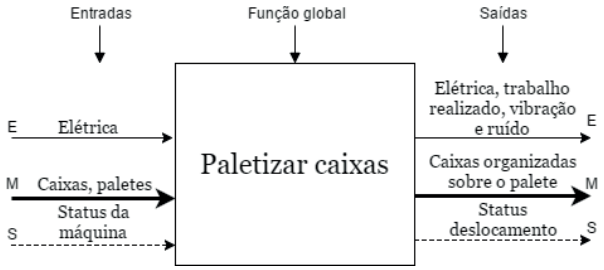

Fig. 2. Esquema da estrutura global

T8 – Definir as subfunções do produto: Desdobrou-se a função global até chegar às funções elementares, salientando as diversas funções que a integram. Elas posteriormente serão usadas na matriz morfológica, simplificando a próxima etapa do projeto.

T9 – Desenvolver princípios de solução: Depois de identificar as subfunções do produto, nesta tarefa determinou-se diversos princípios de soluções para cada função da estrutura funcional do produto. Com a tarefa executada, esses princípios devem ser combinados, efetuando-se várias formas de alternativas e soluções.

T10 – Desenvolver alternativas de solução e selecionar a mais adequada: Depois de conhecido os princípios de solução, determinou-se as alternativas de construção segundo os princípios de solução mais compatíveis, que atendam a caracterização do projeto e tenham combinações promissoras. Com essa matriz, apresentam-se quatro alternativas de soluções julgado promissoras, que posteriormente serão estudadas na matriz avaliação. Nem todas as alternativas foram analisadas na matriz de avaliação, por não ser viável tecnicamente e/ou economicamente.

Determinou-se uma concepção como referência que deve gerar menos dúvidas sobre o funcionamento e é então defrontou-se com as concepções restantes. Define- se qualquer concepção que alcançar uma contagem total maior que a referência para prosseguimento do projeto.

Para diferenciar as soluções, foi atribuída uma nota entre -3 a 3, conforme discussão com a equipe de projeto. Após isto é multiplicado com o peso relativo dos requisitos do cliente já apresentados na tabela 1 e realizado um somatório para indicar qual a melhor solução. Aplica-se nesta tarefa a matriz de avaliação, também conhecida como método de Pugh.

Conforme tabela 3, a concepção 2 obteve maior pontuação entre as outras soluções, que apresentou as principais vantagens como: qualidade do equipamento; dimensão reduzida, o que facilita a instalação de diversos equipamentos em série; design do equipamento com as sua forma física e funcionalidades atraentes.

Tabela 3. Requisitos dos clientes

Requisitos do cliente	Peso relativo	Soluções 1 (REF)	2	3	4
Simplicidade na operação	3		-1	-2	+1
Baixo custo de aquisição	3		-1	-2	0
Qualidade do equipamento	4		+2	+1	+1
Segurança na operação	5		+1	+1	0
Dimensões (layout)	3		+2	-1	+1
Durabilidade dos componentes	5		0	+1	-1
Alta tecnologia	3		+1	+1	-1
Ergonômico	4		+1	0	0
Design do equipamento	2		+2	+1	+1
Robustez	4		0	-1	+2
Alto desempenho funcional	5		+1	+1	+1
Peças padronizadas	5		0	-1	-1
Baixo ruído	5		+1	+1	-2
Utilizar o menor número possível de					
Fácil Instalação	3		0	-2	-1
Fácil manutenção	4		-1	-1	+1
Dispensar mão-de-obra especializada	4		-1	-2	0
Minimizar impacto ambiental	4		+1	0	+1
Total +		0	10	8	8
Total -		0	4	8	5
Peso total		0	34	-5	7

Legenda:

+3 quando a solução é atendida de modo imensamente superior à referência
+2 quando a solução é atendida muito melhor que a referência
+1 quando a solução é atendida melhor que a referência
0 quando a solução é atendida tão bem quanto a referência
-1 quando a solução não é atendida tão bem quanto a referência
-2 quando a solução não é atendida muito pior que a referência
-3 quando a solução não é atendida de modo imensamente inferior à referência

4.3 Projeto Detalhado

Na etapa inicial desta fase dimensionou-se os SSC's e simultaneamente a criação de seus detalhamentos. Portanto, para a escolha dos materiais definiu-se um equipamento fabricado em AISI 304, com propósito de evitar a oxidação precoce. Para os perfis de deslizamento escolheu-se como material o PEAD (Polietileno de alta densidade) por se tratar de um material que exerce sua função e tem um baixo custo comparado aos demais polímeros. Em relação aos tubos de recolhimento da plataforma, selecionou-se o material de alumínio, pois tem boa resistência e baixa densidade, diminuindo o esforço dos motoredutores que tracionam a plataforma.

T11 – Dimensionar SSC`s: Os cálculos servem para averiguar as especificações realizadas no projeto conceitual. Devem-se considerar os componentes e características mais decisivas para satisfazer os requisitos do produto [15].

Nesse contexto, utilizou-se para alguns SSC's, o SolidWorks Simulation, que é capaz de testar e auxiliar a tomar a melhor decisão. Este software possibilita a análise das tensões, deformações e deslocamentos as quais os SSC's estão submetidos, não sendo necessário a produção de protótipos.

T12 – Projetar SSC`s: Para o desenvolvimento dos desenhos e documentações dos SSC's da paletizadora projetou-se com o SolidWorks como software de CAD. O equipamento completo está representado na (Fig. 3).

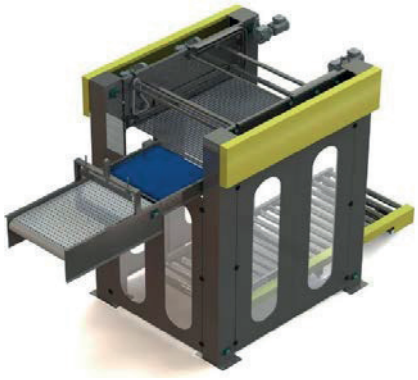

Fig. 3. Paletizadora de caixas desenvolvida em projeto 3D

O processo de funcionamento da máquina paletizadora inicia-se pela esteira viradora, a qual, recebe as caixas da linha de produção. Esta caixa deve estar centralizada e com uma distância considerada entre outra caixa para um bom funcionamento do equipamento. A sua função é girar as caixas em 90º, 180º ou 270º. Utiliza-se um sistema de acumulação para não ocorrer alguma adversidade no conjunto de paletização.

Após a caixa deixar a esteira viradora, ela é transportada na esteira de aceleração. Sua função será de despachar a caixa com uma velocidade maior do que de entrada para que a próxima etapa de paletização (empurrar caixas) ocorra sem haver imprevistos.

O conjunto principal, desenvolve uma função bastante importante no paletizador. Suas funções são de empurrar as caixas para formar a camada, descer o conjunto secundário próximo ao palete, comprimir a camada em todos os sentidos e recolher a plataforma para que a camada seja colocada cuidadosamente sobre o palete.

Empurram-se as caixas lateralmente para que outras caixas ocupem o lugar delas, formando uma camada. Emprega-se um sistema com atuador pneumático para função, por alcançar altas velocidades e ser de fácil armazenagem e transporte. Formada a camada, o conjunto secundário é transportado próximo ao palete por correntes tracionados.

Com o conjunto secundário já próximo ao palete, deve ser recolhido para que a camada fique em cima do palete. Este conjunto é composto por vários roletes fixados em duas correntes. As caixas que compõem a camada são transportadas com os roletes até determinado local, onde se deparam a uma peça com objetivo de manter elas no espaço delimitado. Simultaneamente, as camadas são comprimidas e posicionadas em local específico semelhante à disposição do palete.

Utiliza-se o transportador de palete para movimentar a carga até um ambiente de fácil retirada por equipamentos apropriados para o serviço. Assume a função de base quando o conjunto secundário ainda está em funcionamento e deve ser guiado no momento de posicionar o palete sobre o transportador. É composto por um conjunto de roletes suportado por mancais de deslizamento. As rodas dentadas dos roletes são ligadas em pares. Por se tratar de um conjunto de corrente, devem-se utilizar carenagens que assegurem a proteção recomendada. Projetou-se um sistema de elevação enclausurado, com propósito de diminuir riscos de acidentes a operadores.

Como principais características deste equipamento, tem-se: baixo custo comparado com modelos robóticos; uso de esteiras e corrente, facilitando a manutenção; diminuição das subfunções comparadas aos demais equipamentos; transferência das camadas movendo-se próximo ao palete, que tem posição fixa, a fim de diminuir o esforço dos motoredutores; redução no espaço físico utilizado para localização do equipamento, possibilitando instalar outros equipamentos, ou aumentar o local de transporte de cargas e/ou movimentação de pessoas.

5 Conclusão

Para atender as necessidades dos clientes, o PDP baseado no modelo de [15], torna-se primordial para lançamentos de novos produtos, almejando a superioridade comparando-se com os demais concorrentes. As atividades do PDP proporcionam o desenvolvimento do projeto com mais segurança diminuindo as incertezas e facilitando as escolhas, proporcionando um produto final com tempo reduzido no desenvolvimento, qualidade e preço competitivo no mercado.

O tema selecionado tem sua relevância para automatizar o processo de paletização, tão comum em diversos tipos de produtos. A partir do uso de um equipamento desenvolvido neste artigo e consequentemente o afastamento do sistema manual, obtém-se a diminuição dos problemas ocorridos por doenças ocasionadas a partir de esforços repetitivos e alcança melhorias significativas ergonomicamente. Visto que o sistema manual pode-se tornar o gargalo em uma linha de produção

A automatização do processo reduz os números de colaboradores nesta função, sendo assim, podem ser deslocados para outras atividades e minimiza os erros ocasionados por pessoas.

Portanto com a utilização do modelo PDP no desenvolvimento do projeto, percebeu-se maior facilidade nas resoluções dos problemas e na divisão das tarefas e atividades possibilitando o desenvolvimento com simplicidade e segurança.

As atividades futuras do artigo estão relacionadas ao detalhamento do plano de manufatura, uso de novas ferramentas, como FMEA e elaboração de um manual de utilização e manutenção.

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Teaching Artificial Intelligence using Project Based Learning

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Abstract. This work presents an active learning methodology called Project-based learning (PBL) for developing artificial intelligence (AI) in a computer vision course of an undergraduate engineering degree.

The objective of the course was to develop image recognition capabilities using Deep Learning (DL)/Machine Learning (ML) technics in real-world problems. The PBL learning methodology helped students search for real-world problems, develop complex solutions, and generate synergy among team members. The main role of the professor was to advise, guide and motivate the students throughout the course. The pedagogic innovation with active learning methodologies offered the professor the opportunity to create a dynamic motivating learning environment based on experiences. Each undergraduate engineering student had the opportunity to develop the skills and techniques of their profession: teamwork, proactivity, innovation, and leadership. The results obtained by the student teams showed problem-solving, including the use of automatic navigation equipment with AI, detection of the malaria parasite, recognition of non-human individuals to control vehicular traffic.

Keywords: artificial intelligence, artificial neural network, image recognition, machine vision, project engineering.

1 Introduction

Learning AI technics establishes new challenges to teaching at the university level. Technological changes reduce the life cycles of products and services [1]; The professor and the students must incorporate new technics to their competences during the elective period. [2] presented the PBL methodology for learning computer vision: its main advantages are associated with motivating students to undertake individual and team-based learning, the discovery of new concepts, and the capacity to develop real-world problems by presenting a simple problem [3].

The weaknesses of the PBL methodology regarding the difficulty to establish levels of compromise and learning with all students are mentioned in [4]. However, the PBL methodology [5]–[12] characteristics are defined by a variety of components and reduce the desertion, lack of motivation, or self-esteem of the students [13]–[16]. The components of the PBL philosophy established by the authors [17]–[19] are (1) define a problem starting point, (2) organize the projects, (3) define the teams, (4) guide or advise the participants -by the professor-, and (5) establish interdisciplinary learning.

The PBL methodology has a great capacity to address varied problems in engineering: design of software systems [20]–[24], electric systems [25]–[28], energetic systems [29], [30], microelectronics [31]–[33], medical applications [34], [35],structural engineering [36], [37] and mechatronics [38], [39].

The capacities of the university laboratories allow engineering students to develop and implement complex Works. Over the last years, DL/ML technics have allowed images of the multiple databases to be identified and classified accurately [40], [41]. The selection of the image classification technique must consider the response times, the accuracy of the image or video categorization, the energy expenditure, and the image size and analysis method [42]. The image recognition techniques recognized for their precision and analysis speed are YOLO [43] and single shot detector (SSD) [44] based on end-to-end algorithms, and the region proposal method with convolutional neural networks (CNNs) [45].

The authors of [10], [46]–[49] present works undertaken by undergraduate students through the integration of educational objectives of science, technology, engineering, and math (STEM). The support of experts allows teams of motivated students to be developed, using easy access technological capacities such as Raspberry [50], Python [51], and low-cost sensors and controllers [52]. Some complex problems addressed in these semester courses are autonomous drones [53], robotic arms with AI [46], and DL for classification of image data bases [54]–[56].

2 Materials and methods

The cooperation among students for [57], is a powerful tool in complex environments and develops learning abilities and professional skills among students. The traditional teaching methods limit the movement of students: [57] indicate the dramatic change in the learning environment and the participant requirements at the classroom with active methodology techniques.

The teaching of engineering and sciences through the creation of a functional product should improve by using the main characteristics of the PBL methodology; (1) small student work groups, most of the time, without the presence of a tutor, (2) realistic, professional and large magnitude tasks, (3) tasks that cover only a small part of the class contents, (4) reading to deepen the technical content, (5) group work oriented towards a product, (6) learning new knowledge and abilities, (7) dividing tasks to obtain better products, (8) improving abilities that are strongly interrelated with other courses from the training, (9) focusing on the project work and less on the class,

(10) individual responsibility -critical for project development-, and (11) assessing the final developed product [58]–[60].

The application of the PBL methodology transforms the professor´s role, which is to guide workgroups. [61] points out the need to perform large scope work focused on the student, with collaborative workgroups to solve real-world problems. The obtained knowledge and skills are required for self-management, teamwork, leadership, time management, communication and problem-solving, and the ability to use technology-based tools [62]–[65].

This model allowed responsibilities to be assigned to different student groups, who are transformed into active actors of their education [66]–[68].

The project approach -disintegrating the project into delimited problems- facilitates teamwork, creates task specialization, and increases the depth of the content applied by the teams [69]–[71].

The final objective of the course is to establish a work team, search for a real-world problem and solve it using DL/ML technics for the classification of images. The project was addressed from the engineering perspective, developing (1) the design and engineering of the product, (2) the technical studies, (3) the software engineering (4) the prototype and (5) the functional tests of the product [72]–[74]

2.1 Course Description

During semester planning, the third-year AI class was considered, supported by one professor and two students in their last year of study. The activities were established on a schedule with weekly deliveries of convergent activities. This model allowed multiple activities to be performed in parallel; speeding up the project term [75], [76]. The student teams (3 to 5 people) could choose problems based on their technical abilities, skills, and intellectual interests.

The development of the course was performed in a laboratory composed of one computer per student. The DL technics were prepared and presented by the teams using the PBL methodology. Each exhibition was followed by a feedback activity from the professor and questions from the other teams. The weekly activity included a discussion regarding project portfolios and their possible technological solutions.

Finishing the first stage of 6 weeks, the teams presented their chosen project, the state-of-art of the problem, and the technics required for the solution.

During the second stage of the course, lasting 8 weeks, students established two forms of communication, (1) the communication between each team and the teacher to receive advise on the most difficult points of the project and (2) communication between all the teams and the professor in the classroom. This communication in classes is essential to ensure the delivery of all the technical course content, and peer learning; it is necessary to stimulate opinions among the groups to reduce the learning curve for project development.

Finally, in the third 2-week stage the students must validate their prototypes, deliver the project documentation and give a final presentation with a functional prototype.

2.2 Computer Vision Projects

The computer vision projects selected by the teams addressed a variety of problematics, from automation of naval autonomous equipment with AI, detection of the malaria parasite, and recognition of non-human individuals to control vehicular traffic.

All the teams presented their functional prototypes of image classification at the end of the course.

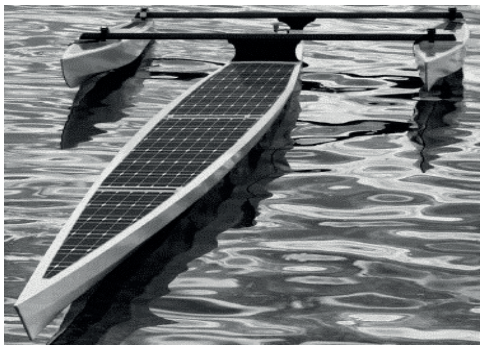

Fig. 1. Prototype of a manned auto embarkation, fed through solar energy

3 Result and discussion

Over this last decade the advances in the design and construction of autonomous marine robots improved substantially for the application to exploration, oceanographic science, and marine engineering. The remote vehicles must be controlled by human operators in real time. This work is laborious and repetitive: the operators must be highly trained to face complex trajectories and recognize the marine environment [45].

The autonomy of the marine equipment can be addressed using acoustic and visual sensors. The use of acoustic sensors is widely used in marine applications, however, the visualization of marine elements at close distances to the boat, require the use of visual sensors [77]. The use of the computer vision technique known as DL precisely identifies marine equipment, marine fauna, and landscapes. These visual sensors must have the capacity of image recognition based on computer vision technics [78], [79].

For the recognition of floating objects an open-source library for automatic learning -called TensorFlow- was used (version 1.7 compatible with operative systems of 64bits as Ubuntu 16.04), which can build and train neural networks. To initiate neural training the open-source model called MobileNet was used: it provides an efficient vision for mobile devices, using an entry resolution of 224 pixels and with relative sizes [80]. The technological solution was installed in a Raspberry Board to analyze the surroundings and command of the anti-collision system of the autonomous embarkation (Figure 1).

3.1 Project Materials and Methods

The start of neural training was carried out on a Notebook Lenovo Ideapad 110 (Processor 2.5 GHz and storage capacity of 1 TB). MobileNet was set to select images of 224 pixels that even though they provide better resolution and require more processing time, will deliver higher classification accuracy. Acceptance of these images in relative sizes will be established in the settings.

Along with the setting process, the monitoring tool TensorBoard that comes incorporated in Tensorflow will also be activated. The selection of the neural network model was done by taking into account some restrictive system parameters with 1 Gb of RAM memory and a 32 Gb memory disk that comes in the Raspberry Pi-Plate [81], [82], to use the trained network with its updates. The selection of the Raspberry-MobileNet system is associated with low energy levels to detect objects in real-time.

The retraining is executed by loading the image databases that were prepared for the initial layer. Considering restrictions of visible light from 500 to 700 nm, the position of the camera where the sun does not obstruct the image capture and the size/visibility of the object, excluding images during the night, with visibility below 400 nm.

Each category can contain a minimum of 20 images [83] (with no size distinction), in this case, a repertoire of 300 images was included in a category in ".jpg" format, obtained from "image-net.org" and from "google images", considering a training of 500 steps. Retraining can extend up to 4.000 iterations, this method is used to improve test performance; the results obtained in the training did not detect performance variations using both kinds of iterations.

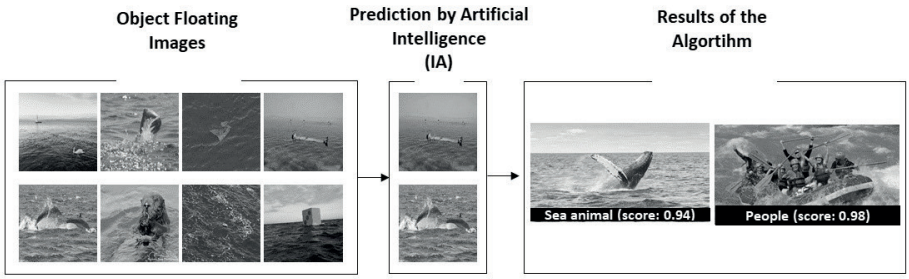

Fig. 2. Diagram of predictive model by artificial intelligence

Test procedure: for retraining the following stages were followed (Figure 2): (1) retrain through the loading of images, (2) results of the neural training with categories included, (3) experimentation with external images to those used previously, (4) results of floating object recognition [84].

3.2 Project Results

In figure 3 and table 1 the validation accuracy of the images or the percentage of images correctly labeled are displayed. The X axis shows training progress, and the Y axis shows the accuracy for entry resolution at 224 pixels for the different relative sizes used in the training tests of floating objects (0.25, 0.50, 0.75 and 1.0).

The Train line presents the accuracy of the training data model, while the validation line shows the accuracy of the set of tests. For this case, the train graphics have an upward trend, while the Validation graphics are below them; the model is over adjusted and starts memorizing the training set instead of understanding the general patterns in the data.

For this experimental phase, the progress of the model´s cross entropy must be analyzed to understand the improvement of the learning process.

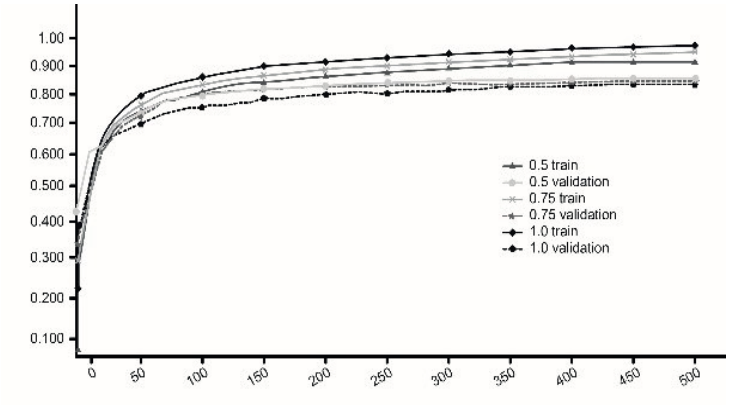

Fig. 3. Occurrence graphic by sizes relative to MobileNet

The objective of the training is to reduce the loss to ensure learning: keeping the declining trend through the discard of short-term noise.

Table 1. Accuracy data of the model.

Name	Smoothed	Value	Step	Relative
Mobilenet 0.50 224/train	0.9195	0.9700	499.0	15s
Mobilenet 0.50 224/validation	0.8497	0.8500	499.0	15s
Mobilenet 0.75 224/train	0.9447	0.9800	499.0	15s
Mobilenet 0.75 224/ validation	0.8439	0.8900	499.0	15s
Mobilenet 1.0 224/train	0.9716	0.9400	499.0	16s
Mobilenet 1.0 224/ validation	0.8348	0.7900	499.0	156s

The script executed 500 training iterations. Each step chooses ten images at random from the training set with its bottlenecks (penultimate layer responsible for classifica-

tion) in the cache and introducing them into the final layer to obtain predictions. Those predictions are compared to the real labels to update the weights of the final layer through the backward propagation process. The repetition of the process improves the accuracy of the neural network. Once the experiment is finished a final evaluation of the test accuracy is performed with a set of new images. This test evaluation is the best performance estimation of the model trained in the classification task. The accuracy values vary between 80% and 95%. Each experiment modifies the predictive capacity due to the random character of the neural process in the selection of images. The results are represented in figure 4; in the X axis shows the quantity of iterations, Y axis the accuracy of entry resolution 224 pixels with the different relative sizes evaluated (0.25, 0.50, 0.75 y 1.0).

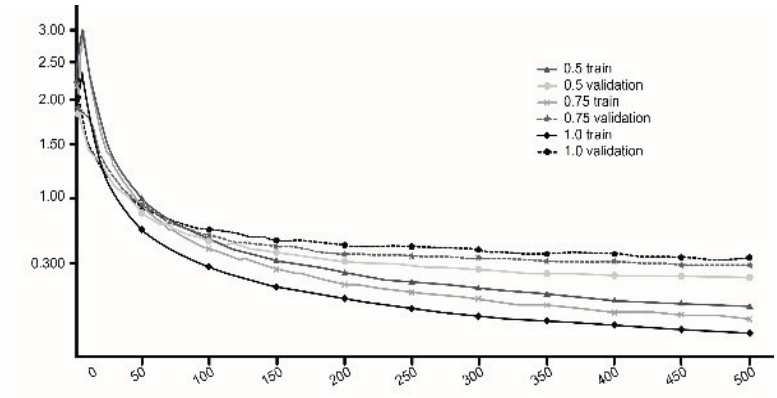

Fig. 4. Graphic of entropic cross by relative sizes at MobileNet

The great number of samples in the database provides the algorithm with a better opportunity to learn and provides a more specific database for training, which in turn allows the accuracy of the model to be improved [85], [86]. Finally, the obtained results with the modified CNN are compared with the results obtained using others benchmark CNN trained for the detection of floating and non-floating objects [87]–[89], obtaining improved performance in the recognition and classification of images. Table 2 presents the test results of the selected categories, which can be compared with the retraining results of a network, achieving better results than non-trained networks [90].

3.3 Project Discussion

We trained a CNN to detect floating objects in the sea for the navigation of a manned auto embarkation, powered by solar energy with a Raspberry central system. The results of the proposed CNN training were better than the results obtained from the compared CNN. This supports future work towards the optimization of the behavior of autonomous boat decisions, for example, by measuring the distance, size and relative speed of floating objects. We expect this experience to help practitioners in the

process of retraining the CNN and in the application of this method to improve the image's recognition process.

Table 2. Average percentage of the recognition assertiveness of objects for the applied methodology.

Category	TensorFlow CNN re-train	MatLab	Inception	Yolo
Boat	0.9642	0.7595	0.3033	0.7420
Dock Maritime	0.8634	0.20000	0.5012	0.0000
Iceberg	0.9140	0.6000	0.0000	0.0000
Obstacle	0.9714	0.6000	0.0791	0.0000
People	0.9381	0.6800	0.0000	0.7960
Sea Animal	0.9675	0.8200	0.8376	0.0000
Submarine	0.9995	0.9195	0.4692	0.1200
Waterfowl	0.9724	1.0000	0.2720	0.8300
Eave	0.9714	0.4800	0.3508	0.0000

Detection and recognition of floating objects in the sea is a theme of great importance in the fields of civil protection, environmental care, and applications for maritime navigation. In this study, we proposed retraining CNN that detect floating objects in real-time using the prototype of an autonomous navigation vessel, fed through a solar energy system. For the detection of floating objects, a neural network was trained in 9 categories which were compared with other existing methods, achieving superior levels of recognition than the proven methods.

3.4 Assessment

The competencies assessed in each project correspond to the tuning model for Latin America. The assessment model considered a matrix activity with learning results. Assurance of student learning was achieved through the compliance of the learning factors [91], [92]. It used a series of questions qualified by the 5-point Likert scale and seeks to compare the different variables between the projects developed during 2019 using the master class learning methodology with the execution of individual AI projects versus the AI project using the PBL methodology. The results are shown in Table 3.

To establish the effectiveness of the PBL method, a control group was established (35 students) to execute a null hypothesis of equality of means among the averages of the control group using the learning method of masterclasses and the course with PBL methodology (42 students). The statistical test was rejected when the average of the

course with the PBL methodology was higher than that of the course used as a control group.

Both groups started the semester with an initial knowledge test and the accepted hypothesis test; the two groups had similar knowledge at the beginning of the semester.

Table 3. Results of student's self-assessment using five-point Likert surveys of master class learning group (35 students) and the PBL group (42 students)

Question	PBL Mean	Master Class Mean
Did you apply your abilities of abstraction, analysis, and synthesis during the development of the project?	4.3	4.0
During the development of the project, did you delve into knowledge and experience of the study and profession field?	4.0	3.5
During the development of the project, did you improve the way you communicate in another language?	3.0	1.5
During the development of the project, did you develop your abilities to use technology and communication tools?	4.8	4.5
During the development of the project, did you increase your ability to search and analyze information from several sources?	4.3	2.5
During the development of the project, did you increase your ability to motivate and work around a common goal?	4.5	2.0
During the development of the project, did you feel that your ability to work independently improved?	4.1	2.5
During the development	4.1	2.6

of the project, did you think your ability to formulate and manage projects improved?	

The student's perception, reflected in survey's results, is aligned with the subject and the graduation profile objectives: To acquire the necessary knowledge, skills and attitudes to perform in the management, and the improvement of production and services systems; in administrative management, entrepreneurship and innovation; and in organization's strategy context, applying their ability to lead interdisciplinary teams, and their theoretical and practical knowledge in the Engineering field.

Teachers positively evaluate self-management, leadership, and creativity developed by students during activities inside and outside of class. In particular, the considerable increase in communications and interactions between peers and teachers outside of class time. These self-managed activities by student teams to achieve project goals are supported by oblique communication platforms such as social networks.

The expected result of learning using the PBL technique is that students know the concept of neural networks and artificial intelligence, its components, the research on its applications, and the recommendations about its use.

4 Conclusions

Through PBL, engineering students developed the design of the product, (2) the technical studies, (3) the software engineering (4) the prototype and (5) the functional tests of the product. This multidisciplinary work allowed students to quickly join the management of complex engineering projects.

The model proved to exceed the traditional model for large magnitude projects; most of the students complied with the due dates of the assigned tasks, demonstrating an appropriate level of work and commitment with the project. At the beginning, the students felt lost when facing a new work methodology; professor guidance secured their curiosity and interests to highlight their selected areas, providing support to other teams, and reaching the finish line as a large team.

PBL driving force might be copied in other complex projects for different study areas; this contributes to the development of personal skills, teamwork, leadership, autonomy, and personal initiative.

Finally, the university directives established an economic contribution to develop the active learning methodology in other engineering courses. The reuse of knowledge and techniques learned by students and teachers allows increasing the technological defiance for higher engineering courses, reducing the learning time in student teams.

The students perceptions during the development of the course with the PBL techniques are opposed, they accept and reject the method; the analysis of the experiences will allow us to visualize the benefits and propose continuous improvement of the learning process.

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Abordaje de conceptos de matemática en proyectos interdisciplinarios

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1 Abstract extendido

El aprendizaje por proyectos es un tipo de propuestas pedagógico-didáctica tendiente a favorecer la apropiación de saberes por parte de los estudiantes, y esto para todos los niveles educativos [1],[2],[11],[12][16],[18].

En particular, en enseñanza de la matemática, el aprendizaje por proyectos suele interceptarse con otro enfoque, el que se interesa a la modelización. Esta última siendo entendida como una suerte de proceso con potencialidades didácticas que relaciona un contexto real con un conjunto de conceptos abstractos.

En este sentido, se destaca el denominado ciclo de modelización que comienza en una problemática de la realidad, luego se sintetizan sus características y variables fundamentales acorde al problema a resolver, a continuación esas características y variables son puestas en relación en un modelo a los fines de producir razonamientos y conclusiones que serían imposibles o muy difíciles de alcanzar por observación directa del contexto de referencia. A nivel didáctico siempre, se insiste en la importancia que esos razonamientos producidos en el modelo regresen al contexto de referencia que motivó su convocación y esto con la intención de facilitar la atribución de sentido al aprendizaje por parte de los estudiantes [3],[5],[8].

A su vez, existe consenso tanto en la complejidad como en la riqueza de los conceptos de matemática que los docentes abordan con sus estudiantes. Para dar cuenta de esa riqueza y complejidad, algunos autores introdujeron el concepto de registro semiótico [6],[7],[14][15], destacando que muchos de los saberes, para su integral comprensión, deben ser aprendidos en los diferentes registros en los cuales ellos se manifiestan. Así es posible identificar el registro numérico, el gráfico, el simbólico, el coloquial, etc. Todos necesarios de ser transitados para una apropiación integral de los conceptos por parte de los estudiantes [4],[10],[13].

En esta comunicación compartiremos algunos resultados obtenidos en el marco de un proyecto de investigación acreditado y financiado por la Universidad Nacional de Río Negro (UNRN), Argentina, donde nos interesamos a analizar las potencialidades que presentan los proyectos interdisciplinarios para abordar, en particular, conceptos

de matemática. Para ello, durante el año 2018 se llevó a cabo un proyecto con estudiantes de la Tecnicatura Superior en Mantenimiento Industrial (TSMI) en la cátedra de Matemática consistente en el cálculo, construcción e instalación de molinos del tipo Savonius [17]. Este proyecto fue financiando por la Secretaría de Políticas Universitarias (SPU) en tanto que proyecto de extensión.

La potencialidad aquí retenida trata sobre las posibilidades que permitió el proyecto de abordar conceptos de matemática en sus diferentes registros semióticos en el contexto de modelizaciones que respondían a demandas del proyecto. Para ello, el equipo de investigación se basó principalmente en tres tipos de fuentes: registros de audios de clase, registro de notas de los dos docentes a cargo de la cátedra y archivos en Geogebra y Hoja de cálculo producidos en clase.

La figura 1 ilustra el tipo de molino al origen del proyecto interdisciplinario desarrollado con los estudiantes de la TSMI. Cabe acotar que la cátedra de matemática, es del tipo cuatrimestral (desde Marzo a Junio), su plantel docente está compuesto por un investigador en didáctica de la matemática (autor del artículo) y un ingeniero civil. Los estudiantes por su parte, ingresantes a la carrera, son de orígenes muy variados y con edades comprendidas entre los 18 y los 50 años. El grupo suele tener una proporción de mujeres de aproximadamente el 25 por cierto.

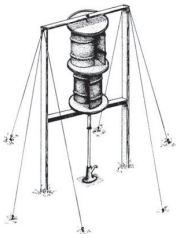


Fig 1. Esquema de Molino Savonius

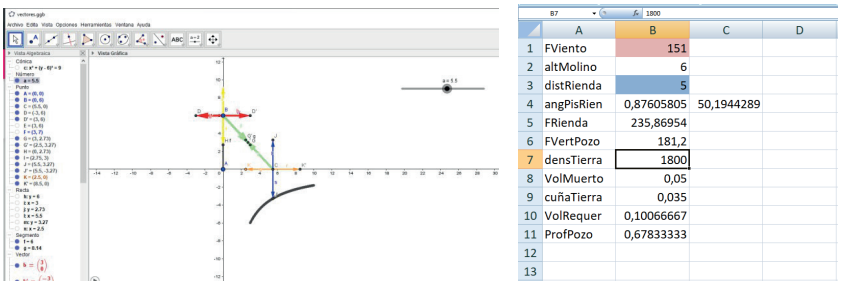
El enlace de abajo envía a un vídeo corto donde puede observarse la instancia final consistente en la instalación de dos molinos por parte de los estudiantes de la TSMI, uno en un puesto rural (La Margarita) en cercanías de la localidad de El Cuy, el otro en un puesto rural (Horno Viejo) perteneciente al ejido de Sierra Colorada.

https://www.youtube.com/watch?v=889fvPzVK1g

La potencialidad observada consistente en la posibilidad de abordar conceptos de matemática en diferentes registros semióticos por medio de modelizaciones se observó en reiteradas oportunidades. Por razones de espacio se sintetiza aquí solo un caso: el referido al estudio de las riendas tensoras del molino. Ese estudio se realizó en dos softwares, uno llamado Geogebra (www.geogebra.org), el otro en Hoja de Cálculo.

El estudio en Geogebra respondió a una necesidad del proyecto de analizar, si las riendas tensoras soportarían diferentes esfuerzos en caso de anclarlas, por necesidad, más cerca o más lejos respecto del molino de lo originalmente previsto. El estudio en

Hoja de Cálculo se orientó a determinar la profundidad del pozo donde se anclarían las riendas tensoras.



	A	B	C	D
1	FViento	151		
2	altMolino	6		
3	distRienda	5		
4	angPisRien	0,87605805	50,1944289	
5	FRienda	235,86954		
6	FVertPozo	181,2		
7	densTierra	1800		
8	VolMuerto	0,05		
9	cuñaTierra	0,035		
10	VolRequer	0,10066667		
11	ProfPozo	0,67833333		
12				
13				

Fig 4. Captura de pantalla de estudios realizados en Geogebra y en Hoja de Cálculo

Por razones de espacio, nos limitaremos aquí al concepto de vector abordado en las dos modelizaciones y sus tres características: dirección, sentido y módulo. El estudio en Geogebra fue del tipo relacional: luego de la construcción, un deslizador controlaba la posición del punto de anclaje y la opción rastro de Geogebra permitía observar la variación de los esfuerzos en función de la ubicación de la rienda. En la vista gráfica, no solamente se abordó el concepto en el registro semiótico gráfico ponderando aspectos referidos a dirección y sentido, sino que también se observaron nociones vinculadas a descomposición de vectores, equivalencia, y relación entre módulos. En la vista algebraica por su parte, los vectores fueron representados en el registro numérico y simbólico por sus coordenadas cartesianas.

Por su parte, el archivo en Hoja de Cálculo, al tener el objetivo de determinar la profundidad del pozo en función de un conjunto de variables, entre ellas la distancia de anclaje, se abordó el módulo de vectores en el registro numérico y algebraico [9].

En otras palabras, ambos estudios se complementaron no solo para abordar las nociones de dirección sentido y módulo sino también para tratar el concepto de vector en diferentes registros semióticos.

A modo de síntesis y en función de lo observado en el proyecto llevado a cabo, los proyectos interdisciplinarios pueden resultar un contexto rico en posibilidades de abordaje de conceptos disciplinares, en particular de matemática. Las modelizaciones poseen la potencialidad de analizar el contexto de referencia y de facilitar conclusiones que serían prácticamente imposibles de elaborar de manera intuitiva. Por último, destacamos que las modelizaciones realizadas resultaron de utilidad a las cuestiones a resolver en el proyecto, por lo que el ciclo de la modelización se realizó de manera completa.

A modo ilustrativo, en la instalación del molino en el puesto Las Margaritas, los pobladores realizaron los pozos más cerca de lo previsto. Se pudo observar a los estudiantes debatir y recuperar la modelización en Geogebra y acudir al archivo en Hoja de Cálculo disponible en sus celulares para determinar la profundidad a la que deberían estar los pozos (en el min 0:32 puede observarse a los estudiantes aumentando la profundidad de los pozos). Ese ejemplo de utilización en el campo, representa el fun-

cionamiento del ciclo de modelización donde los conceptos no solo son de utilidad para comprender fenómenos sino también para intervenir en ellos.

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Reestructuración del dictado de materias de Matemática en las carreras de Ingeniería en Alimentos e Ingeniería en Biotecnología

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Resumen. Este trabajo se basa en una primera experiencia académica sobre el dictado de las materias del ciclo superior de matemáticas complementado con el uso y programación en la plataforma OCTAVE. Fue puesta en práctica para las carreras de Ingeniería en Alimentos e Ingeniería en Biotecnología de la Universidad Nacional de Río Negro durante los años 2019-2020.

Palabras Claves. Matemática Superior. Cálculo Multivariado. Métodos Numéricos. OCTAVE. Aprendizaje Virtual en Ingeniería

1 Introducción

Esta adecuación de los contenidos de matemática y la incorporación de elementos de programación en el entorno OCTAVE surge a partir de las observaciones realizadas por los pares evaluadores en la acreditación de la carrera de Ingeniería en Biotecnología de la Universidad Nacional de Río Negro en el año 2018. El dictado de las dos materias de Matemática del ciclo superior (que están en el 2do. año del plan de la carrera referida) se comparte con alumnos de Ingeniería en Alimentos. Durante los primeros diez años de la creación de esta última carrera, se dictaron dichas materias en la forma tradicional, una referida a Cálculo Multivariado y la restante referida específicamente a la temática de Ecuaciones diferenciales ordinarias y en derivadas parciales.

2 Cambios realizados

Los cambios propuestos en el dictado de las dos materias apuntan a satisfacer requerimientos de la Comisión Nacional de Evaluación y Acreditación Universitaria (CONEAU) en Argentina con el fin de nivelar los contenidos de la disciplina con los de carreras análogas de otras universidades nacionales. El principal desafío fue diseñar ambas materias de manera que conjuguen todos los conceptos de Cálculo Multivariado, Ecuaciones Diferenciales y Métodos Numéricos de forma tal que se aborden

con una herramienta de programación donde se desarrollan los cálculos y post-procesamiento de datos necesarios con el fin de que obtengan una visión temprana sobre el alcance de la aplicación de estas herramientas informáticas, que además serán útiles en su futura actividad profesional como en otras asignaturas posteriores de la carrera, tanto sean orientadas al cálculo numérico como las de laboratorio. Bajo esta óptica, la currícula íntegra de estas dos materias, que se dictan en cuatrimestres consecutivos y tienen cargas horarias semanales de 6 hs (A. Cálculo Multivariado) y 4 hs (B. Métodos Numéricos), respectivamente, fue desarrollada en su totalidad pero además adecuada y complementada con el uso de OCTAVE [1] y programación en dicha plataforma. Cabe señalar que por tratarse de un *software* libre, se dispone de tutoriales muy completos en Internet.

A continuación, en los apartados que siguen se mencionan los temas abordados en cada una de las materias (A y B), cómo se fue acoplando la utilización de una herramienta de programación a lo largo de todo el cursado (C. Herramientas de programación), y finalmente, los desafíos y readecuaciones que se hicieron para afrontar las dificultades que la pandemia por SARS-CoV-2 (COVID-19) originó en el cursado presencial habitual de las materias originando el dictado virtual de las mismas (D. De la presencialidad a la virtualidad). Por último, se presentan algunas conclusiones.

A- Cálculo multivariado

El programa de la materia fue diseñado para contener los temas tradicionales de un curso de análisis matemático referido a funciones de varias variables, partiendo un afianzamiento con la geometría del espacio, con las superficies más reconocidas, las operaciones vectoriales más utilizadas para tener una métrica y calcular así distancias y ángulos, y reconocer en ese entorno las ecuaciones de rectas y de los planos. Posteriormente se abordaron los siguientes tópicos: representación de funciones en el espacio, límite y continuidad de funciones de dos o más variables. Una vez finalizados estos contenidos, se desarrolló todo lo referido a la noción de derivadas parciales, diferenciabilidad y aproximaciones de funciones, para concluir este capítulo con problemas de optimización sin y con restricciones. A continuación, se introdujeron conceptos de integración múltiple, incluyendo los cambios de coordenadas más usuales. Este último tema posibilitó el desarrollo de la última unidad de la materia que se refiere a Cálculo Vectorial, que incluye campos vectoriales, integrales de línea y teorema fundamental y de Green, nociones de rotacional y divergencia, superficies paramétricas, integrales de superficie y los teoremas de Stokes y de la divergencia. La referencia bibliográfica básica fue sustentada mediante la utilización del libro de Stewart [2]. Una selección de ejercicios de cada unidad temática fue sugerida para la práctica de los nuevos contenidos.

B- Métodos numéricos

Partiendo de una introducción al análisis del error se analizaron las aproximaciones de valores funcionales empleando las series de Taylor, se introdujo la derivación numé-

rica para evaluar la medida del error cometida con las distintas expresiones que se emplean y también se calcularon aproximaciones de raíces por el método de Newton, entre otros. En segundo lugar y referido a problemas de trabajo con matrices, se estudiaron distintos métodos de resolución de sistemas lineales incluyendo los que usan la descomposición LU, Gauss-Seydel y Jacobi, apuntando al trabajo con sistemas de grandes dimensiones. Un capítulo especial fue dedicado al de aproximación de funciones, considerado regresión lineal y polinómica, polinomios de interpolación de Lagrange y splines cúbicos y además polinomios trigonométricos para el caso de funciones periódicas. En cuanto a ecuaciones diferenciales ordinarias se vieron los métodos más representativos en cuanto a la resolución numérica, como Euler y Runge-Kutta, mientras que se trabajó la resolución exacta por medio de la Transformada de Laplace, que es un tema requerido especialmente para el dictado de las materias de control del ciclo superior de las carreras involucradas. Además se consideraron ecuaciones en derivadas parciales elementales y, por un lado su resolución exacta por medio de separación de variables y los métodos clásicos que emplean series de Fourier y numéricamente aproximando las derivadas con diferencias finitas. La bibliografía básica y clásica adoptada para el dictado de esta materia es el libro de Chapra y Canale [3]. Dada las limitaciones horarias de clase, hay cuestiones temáticas que debieron verse solo abreviadamente o a nivel informativo.

C- Herramientas de programación

De manera simultánea con el desarrollo de los conceptos de Cálculo Multivariado (A) se elaboró un programa de introducción a la programación, donde se abordaron los conceptos de especificación de un problema, generación de un algoritmo, escritura del código e implementación de esquemas depuración de códigos (*debugging*) mediante la trazabilidad de los mismos. Se introdujeron los conceptos básicos de las herramientas de programación como son las sentencias secuenciales, ramificación, lazos y los esquemas de programación modular (funciones).

El esquema de aprendizaje de cada uno de estos temas mencionados se realizó en distintas etapas mediante trabajos prácticos que conectaban gradualmente los temas abordados de Cálculo Multivariado; donde los alumnos incorporaron la sintaxis y semántica utilizada por la plataforma utilizada (OCTAVE), los comandos básicos, clasificación de variables, asignaciones, operaciones matemáticas y manipulación de expresiones y polinomios. A partir de la utilización de los comandos básicos de programación se pudieron realizar operaciones básicas de suma, resta, multiplicación y potencia de vectores y matrices y también se desarrollaron algoritmos que van desde la extracción de submatrices hasta la verificación de propiedades matemáticas. La evaluación de estos trabajos prácticos (tps) se efectuó a partir del envío electrónico por parte de cada uno de los alumnos, de un informe para cada trabajo práctico, incluyendo archivos de tipo *script*, que contenían los comandos necesarios para la resolución de cada ejercicio.

En relación con los contenidos anteriores, desde OCTAVE, en primer lugar se hizo especial énfasis en lo referido a graficación de funciones y trazado de curvas en

dos y tres dimensiones, en particular rectas y planos. Esto permitió representar curvas de nivel y trazas de funciones y también de superficies cuádricas en el espacio. Además, se consiguió visualizar la noción de derivadas parciales y posteriormente los planos tangentes a una superficie diferenciable. La representación de superficies en el espacio tridimensional resultó muy útil para la visualización de dominios de integración y para las aplicaciones de integrales triples. Resulta muy interesante la representación de superficies paramétricas empleando OCTAVE, reconociendo en ellas las típicas curvas reticulares en las imágenes que se obtienen.

Sobre los contenidos abordados en la materia de Métodos Numéricos (B), se observa que los conocimientos sobre la plataforma OCTAVE representan actualmente un alto porcentaje de la materia, puesto que todos los temas mencionados en el apartado, fueron programados y resueltos en ese entorno. Dentro de los ejemplos analizados, se consideraron problemas específicos de aplicación tanto en la industria de Alimentos como en Biotecnología.

Puntualmente, los problemas de ajustes de diferentes curvas de polinomios fueron planteados como problemas de optimización tanto en la plataforma OCTAVE como en EXCEL, donde los alumnos se familiarizaron con los diferentes *solvers* y problemas específicos de la optimización como son los valores iniciales, funciones objetivos, tolerancias de convergencias, entre otros.

De esta manera, debemos destacar que las herramientas computacionales permitieron incorporar y resolver cuestiones de cálculo que no sería posible de abordarlas de otra manera, complementando en forma muy eficaz el proceso de aprendizaje de los estudiantes.

D- De la presencialidad a la virtualidad

Forzados por el contexto de la pandemia mundial por el virus SARS-CoV-2 (COVID-19) nos vimos obligados a recurrir a herramientas virtuales para poder disponer de un ambiente donde los estudiantes y docentes pudiéramos abordar los conceptos y temas propuestos en los planes de las materias mencionados. Todo esto implicó: para los docentes proponer y realizar en tiempo real un cambio rotundo en los aspectos didácticos y pedagógicos acostumbrados para presentar estas materias y para los alumnos un gran esfuerzo de adaptación a la nueva metodología. En esta situación, la conectividad y los sistemas informáticos jugaron un rol fundamental.

Desde la Universidad de Río Negro se cuenta con un entorno virtual que es la plataforma PEMTIC, donde están alojadas sus aulas virtuales. En años anteriores a 2020, el sitio de las materias en consideración en esta plataforma fue utilizado estrictamente como repositorio para la bibliografía y los trabajos prácticos de las mismas y para la comunicación con los alumnos fuera de los horarios de clase mediante el uso de un foro. Esta situación se transformó completamente ante la virtualidad del dictado de las materias impuesta por las circunstancias ya conocidas. Las clases de las materias y las consultas fueron instrumentadas mediante la utilización de la plataforma *Meet* desarrollada por Google, disponible desde la cuenta GSuite de la Universidad, la cual no solo soporta multiusuarios en línea sino que también permite grabar las exposiciones

y realizar presentaciones a todos los participantes mediante la opción de compartir pantalla. En este sentido, los alumnos podían consultar sus dudas y mostrar sus resoluciones al resto de la clase, generando un ambiente más colaborativo que el que se encuentra generalmente en las clases presenciales. Del mismo modo, al concluir las clases teóricas se podían evacuar dudas sobre las presentaciones realizadas ya grabadas, y además, si era necesario se generaba nuevo material con aclaraciones particulares que también era compartido con los alumnos mediante archivos digitales subidos al repositorio del aula. Las clases grabadas se compartían mediante un enlace desde Google Drive después de la finalización de cada clase. Es importante destacar que el dictado de las materias no solo estuvo modificado y adecuado por los docentes mediante el estudio de las herramientas computacionales disponibles, sino que también fue fundamental contar con el soporte a la docencia en la utilización de herramientas tecnopedagógicas. Este sustento fue fundamental para la mejora de la educación a distancia, donde el conocimiento de dichas plataformas educativas facilita al docente la creación de puntos de encuentro para ejecutar las "nuevas" prácticas docentes que se necesitaban en este nuevo contexto y donde también se dispone de un foro de consultas en el que participan docentes de la Universidad y personal profesional preparado para abordar los inconvenientes que pudieran surgir y para promover la utilización de las herramientas disponibles y de las que se han ido incorporando en el último tiempo.

Respecto a las evaluaciones de los estudiantes resultó una cuestión compleja, por cuanto se quiso sostener el formato de evaluación con desarrollo por parte de los alumnos. Dado que estos podían disponer al momento de la evaluación de todo el material dictado en clase, la bibliografía e Internet, entre otras fuentes, las evaluaciones se realizaron conformando distintos grupos de alumnos, elegidos con algún criterio de acuerdo con el desempeño observado durante las clases. Es importante mencionar que las tareas de evaluación fueron ajustadas para ser aplicadas en ambas materias en grupos de estudiantes menores a 15 (quince) alumnos. Dentro de las actividades de evaluación se encontraba el formato *Tarea*, que se encuentra entre las actividades del aula virtual de la plataforma Moodle de la Universidad. La idea de las evaluaciones en cuanto a la parte matemática, apuntaba a resolver ejercicios que no se abordaran mecánicamente, dado que hoy se dispone de *softwares* que resuelven inmediatamente gran parte de los ejercicios tradicionales, solo con un poco de habilidad, y además que demostraran fehacientemente la comprensión de definiciones y expresiones y aplicarán otros resultados teóricos de un modo no automático. De esta forma se evaluaron contenidos por medio de varias tareas, algunas de las cuales tenían el rango de parciales.

Un hecho para destacar dentro de la Plataforma PEMTIC es la incorporación reciente de la herramienta H5P, que permite intervenir presentaciones y videos, entre otras actividades que pueden plantearse a partir de la misma. Esto significa que se puede volver interactivo un recurso de la materia, donde el alumno se limitaba hasta este momento a ver y/o escuchar. De esta forma, con el mismo material empleado en las clases teóricas se pueden generar nuevas actividades como autoevaluaciones, evaluaciones y proponer nuevos desafíos. Ya se realizaron algunos ensayos con esta herramienta H5P interviniendo videos en la materia de Cálculo Multivariado. Se espera

incorporar esta herramienta en las presentaciones de la materia Métodos Numéricos donde se desarrollan los contenidos, a modo de cierre de cada una de las clases semanales, durante el segundo cuatrimestre 2020.

Otra actividad planificada con los alumnos fueron las presentaciones grupales de a dos o a lo sumo tres alumnos. Esta actividad también fue evaluable, donde cada grupo designó un representante encargado de comunicar dudas y preguntas a los profesores. Los temas abordados en las presentaciones estaban relacionados completamente con la utilización de la plataforma OCTAVE y, en algunos casos particulares, sobre otras herramientas de presentación utilizadas que no eran de conocimiento general de los alumnos tanto de Power Point como Prezi. La cantidad de exposiciones realizadas en las dos materias demuestra una sustancial mejora de los estudiantes en el desarrollo de habilidades orales, de expresión y de organización, generando un gran impacto en la motivación y formación de los estudiantes en una etapa temprana de la carrera.

Cabe destacar que todas estas pautas mencionadas son de aplicación en cursos con una cantidad de alumnos no demasiado grande, por lo que cursos numerosos deberían readaptar los ítems mencionados, principalmente en las evaluaciones y exposiciones.

3 Conclusiones

Las adaptaciones del dictado de las materias de Cálculo Multivariado y Métodos Numéricos y los cambios realizados y a nivel de curricular y metodológicos, permitieron dar curso a todas las observaciones realizadas por los evaluadores de CONEAU, en el proceso de acreditación de la carrera de Ingeniería en Biotecnología. La experiencia del dictado presencial de ambas materias en 2019 pudo ser mejorada pese al contexto de virtualidad durante 2020. Las razones que encontramos para justificar estos logros son:

1. Ampliación de las metas en el dictado de la materia de Cálculo Multivariado (A) con la incorporación de contenidos y tareas específicas que hacen al uso y programación en OCTAVE. De no haberse realizado esta tarea durante el primer cuatrimestre, resultaría inalcanzable cumplir los objetivos de implementación de algoritmos en toda la temática de la materia de Métodos Numéricos (B), que se dicta en el segundo cuatrimestre.

2. Mejor organización y aprovechamiento del horario de clases. Se destinó un tiempo a las clases teóricas y otro tiempo de consultas generales. Además, durante el desarrollo de las dos materias y clase a clase, se designaron alumnos para preparar y exponer ejercicios seleccionados de los trabajos prácticos, en la clase siguiente. Esto constituyó también en una actividad individual evaluable y además esto último dinamizó, sobre todo, las clases virtuales, haciendo explícita la actividad y participación oral en clase de todos los estudiantes.

3. Mantener un canal de comunicación permanente con los alumnos.

Por otra parte, entendemos también que la mejoría realizada en el dictado tiene un efecto positivo en el alumnado por cuanto además de los contenidos mínimos que requiere el dictado de estas materias, se ha estimulado el desarrollo de otras destrezas

como son la escritura de informes, la oralidad, la preparación del material para exposiciones con el manejo de herramientas diversas a elección y también el trabajo grupal.

En cuanto al impacto de estas modificaciones en el dictado de ambas materias dentro la carrera, cabe destacar tres aspectos distintivos:

1. Al concluir el ciclo anual, los estudiantes que participaron activamente de este dictado 2020 manejan un conjunto de herramientas especialmente útiles de cara al cursado de materias más complejas que deberán enfrentar en su carrera a partir del próximo año. Esto redundará en beneficio del dictado, objetivos y profundidad de desarrollo de tales materias, dado que la preparación de base del alumnado ha mejorado.
2. Alumnos de esta cohorte, que ya han aprobado o promocionado estas materias son los únicos estudiantes regulares de la carrera en condiciones de desempeñarse en las mismas como ayudantes alumnos y ya han sido convocados a tal fin para el año próximo.
3. Como tarea adicional, se diseñaron actividades para enlazar los contenidos de Matemática de materias anteriores, donde los estudiantes presentaron a sus pares de primer año la metodología de trabajo que enfrentarán en las materias de Matemática de segundo año de sus carreras y además compartieron con ellos la resolución de problemas concretos y que les eran familiares, explicando en forma completa el modo de abordarlos dentro de la plataforma OCTAVE.

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Autoevaluación y Coevaluación para la mejora continua del trabajo en grupo: Aplicación y experiencia en clases virtuales

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Resumen. Sabemos que generar competencias de trabajo en grupo en los y las estudiantes de ingeniería es un desafío latente en los últimos años. Si bien la mayoría de las y los docentes podría asegurar que dan actividades para que se desarrollen en grupo, serían muy pocos/as los/as que dirían que han enseñado a trabajar en grupo. Por otro lado, la actual situación de distanciamiento social y de clases no presenciales ha resultado en un gran número de trabajos prácticos grupales como estrategia de enseñanza-aprendizaje virtual. En este trabajo, se exponen 2 actividades desarrolladas en la materia Gestión de la Calidad cuyas estrategias didácticas se basan en el Estudio de Casos y el Juego de Roles, mediante el trabajo grupal y se utilizan Autoevaluaciones y Coevaluación cómo métodos para el aprendizaje y mejora continua del hecho de trabajar en grupos formados aleatoriamente. En los casos abordados deben aplicar las herramientas AMFE (Análisis Modal de Fallos y Efectos) y el Diagrama de Causa y Efecto (Ishikawa) y QFD (Despliegue Funcional de la Calidad). Posteriormente, todos completan una grilla de auto y co-evaluación, programada en la plataforma Moodle, donde se evalúan aspectos como compromiso, respeto, integración en el grupo, escucha y preparación. Los resultados indican que la experiencia significó un crecimiento personal de la habilidad de trabajar en grupo, principalmente por el espacio de reflexión y retroalimentación generado.

Keywords: Coevaluación, Autoevaluación, trabajo en grupo.

1 Introducción

Desde hace varios años en Argentina la formación universitaria de los y las futuros ingenieros e ingenieras está transitando un camino de revisión de las formas de enseñanza y aprendizaje instaladas [1-2].En este contexto aparece la noción de competencia que pone en el tapete la "pertinencia de una formación que se limita a transmitir las disciplinas teóricas y a desarrollar capacidades generales sin referencia a su contexto de utilización" [3]. Desde esta perspectiva, se busca la formación de profesionales competentes, es decir, para el caso de la ingeniería, de un sujeto capaz de realizar las tareas

requeridas adecuadamente de acuerdo a los estándares de su profesión. Dentro de las competencias requeridas, este trabajo focaliza las denominadas competencias psicosociales, en especial las referidas a las relaciones interpersonales.

El/la profesional en ingeniería en su trabajo diario no solamente se relaciona con otros sujetos, sino que la tarea que realiza necesita del trabajo en grupo o trabajo en equipo[1]. Es amplia la bibliografía que enumera los beneficios del trabajo grupal y la necesidad de que el/la ingeniero/a aprenda el trabajo colaborativo. Es posible plantear que aunque los planes de estudio actuales en muchos casos presentan dentro de las incumbencias de ingeniería la capacidad de trabajar en equipo y de liderar grupos de trabajo [4], sumado al reconocimiento, por parte de los/as docentes universitarios y de los/as estudiantes, del valor que tiene esta capacidad para tener éxito en la labor profesional, la mayoría de los planes de estudio y programas universitarios no incluyen la enseñanza de esta competencia como objeto de enseñanza [5].

¿En qué radica el valor del trabajo en equipo? Desde que nace el hombre aprende a vivir en el mundo por la relación que establece con los otros. El grupo constituye un tiempo y espacio compartido en que construye sus habilidades, conocimientos y valores entre otros que le van a permitir habitar el mundo. A lo largo de la vida participamos en infinidad de grupos y de una forma intuitiva aprendemos a relacionarnos o, cuando no lo logramos, nos alejamos del grupo. Sin embargo, las demandas actuales del mundo laboral exigen que el profesional desarrolle tareas más complejas que demandan una actitud flexible y abierta, producción de conocimiento para dar respuesta a situaciones imprevistas y la participación en la gestión y control de su propia tarea, entre otras [3]. Estos cambios en las exigencias laborales hacen imprescindible el trabajo en equipo como forma colaborativa de trabajo. Sin embargo, la reunión de un conjunto de sujetos no siempre lleva a un trabajo en equipo. Un grupo es un conjunto de sujetos que se relacionan cara a cara con una cierta historia, objetivos compartidos y una trama vincular [6]. Cada miembro tiene habilidades, experiencias y saberes propios, formas de actuar, de sentir y de ver la realidad que resultan enriquecedoras a la hora de resolver una tarea pero que deben articularse, combinarse, manifestarse y ponerse en juego para realizar un trabajo. Es por ello que se hace necesario convertir al trabajo en grupo en un objeto de enseñanza en los espacios de formación profesional.

Una de las estrategias didácticas más utilizadas en la modalidad virtual de enseñanza ha sido los trabajos grupales, ya sean trabajos prácticos, trabajos de investigación, de reflexión, aprendizaje basados en problemas, entre otros [7-10] en los cuales se espera que se resuelva una consigna junto a otros/as, obteniendo un producto final que debe ser entregado o presentado para su evaluación y/o calificación, y que generalmente estas últimas resultan en una devolución general del grupo y no de cada uno de sus integrantes. En este sentido, es importante reflexionar acerca de cómo acompañamos a nuestros alumnos/as en el proceso de aprendizaje de un determinado tema al darles una consigna a resolver dentro de un grupo. La bibliografía y la experiencia nos dicen que el trabajo en grupo generalmente es positivo en relación al aprendizaje. Sin embargo, sabemos que a trabajar en grupo se aprende y que, además, cada grupo es particular y

[1] Aun cuando diferentes autores diferencian el trabajo en grupo con el trabajo en equipo en esta comunicación tomamos como sinónimos ambas expresiones.

pueden haber fuerzas que generen sinergia o por el contrario, que generen división. Tal como menciona Zarzar Charur [11] la dinámica del grupo se define como "la interacción de todas las fuerzas que entran en juego desde el primer momento en que el grupo se reúne, y que van variando en intensidad y dirección".

Si bien en la modalidad presencial, una devolución individual y personal que nutra el proceso de aprendizaje, podría hacerse mediante algún método de observación dentro del aula, claramente si la actividad se resuelve fuera de esta, la observación ya no es un método viable. En ese caso, la autoevaluación y la evaluación entre pares (o coevalaución) son potenciales medios que permiten obtener una evaluación personal de cada integrante del grupo. Lo que se propone es que el control de la evaluación deje de situarse irrevocablemente en las manos del/a docente y se transfiera a los/as alumnos/as. En este sentido, numerosos estudios demuestran que la evaluación confiada exclusivamente al docente, no favorece el proceso hacia la madurez y la creatividad que las instituciones educativas tratan de lograr [12], y que por el contrario, dichos estudios enuncian que la mayor parte de los/as estudiantes aprenden a evaluar su trabajo cuidadosamente, con honestidad e introspección, si se habilitan los medios para valorar su propio aprendizaje y/o el de sus compañeros/as. Los procesos de autoevaluación y de coevaluación permiten orientar al/a estudiante en el rol del/a docente, ya que lo involucra con las peculiaridades del proceso de evaluación, (contribuyendo así, al desarrollo de habilidades en este sentido) y lo/a ubica dentro del análisis del alcance de los resultados de aprendizaje esperados [13].

Entonces las preguntas que surgen son ¿Enseñamos a trabajar en grupo? ¿Damos acompañamiento a dicho trabajo? ¿Ha sido positivo abordar determinado tema desde el trabajo grupal? ¿Aporta la evaluación y la coevaluación al proceso de enseñanza aprendizaje? En el presente trabajo se tuvieron en cuenta dichas preguntas para planificar las actividades grupales a desarrollar durante el cuatrimestre de modo que las mismas sean acompañadas desde la cátedra, procurando enseñar a trabajar en grupo y esperando un efecto positivo de este sobre el aprendizaje de los contenidos.

Los objetivos de este trabajo son presentar una experiencia de aprendizaje grupal utilizando la autoevaluación y la coevaluación, y analizar los resultados y devoluciones de los participantes para mejorar los métodos utilizados, procurando replicar las estrategias utilizadas. El presente trabajo comienza relatando la experiencia de clase desarrollada, su contexto, objetivos de aprendizaje, estrategias didácticas y metodología evaluación. Posteriormente, se publican los resultados de los instrumentos de auto y coevaluación utilizados y se analizan cuantitativa y cualitativamente los mismos, describiendo situaciones generales y particulares encontradas. Por último, se plantean las principales conclusiones obtenidas y los potenciales trabajos futuros ligados a esta experiencia.

2 Experiencia

2.1 Contexto

Los/as participantes de las presentes actividades corresponden a los alumnos de la asignatura "Gestión de la calidad" del primer cuatrimestre del año 2020, situada en el segundo año del plan de estudio de la Tecnicatura en Operaciones Industriales, de la Universidad Nacional del Sur, ciudad de Bahía Blanca, Argentina. La moda de edad del alumnado es de 20 años. Sin embargo, dado que es una carrera nueva pensada para atender la demanda de la industria local, muchas personas que ya se encuentran trabajando en distintas áreas industriales también transitan la carrera, y estas rondan la edad de los 40 años. Por otro lado, dado la división departamental de la Universidad, cabe aclarar que, dicha asignatura también se dicta en el segundo cuatrimestre del quinto año de la carrera de Ingeniería Industrial.

El contexto que caracterizó el desarrollo de clases de la presente experiencia fue la condición de aislamiento social dada por la pandemia COVID-19, que demandó que desde el inicio al final del curso la metodología de trabajo sea virtual y remota. Esta situación llevó a la cátedra docente a pensar distintas alternativas que signifiquen disminuir la distancia con los/as alumnos/as, así como, desarrollar estrategias que sean desafiantes y motivadoras para los/as estudiantes en la modalidad virtual.

2.2 Objetivos de aprendizaje

Considerando las experiencias de clase a desarrollar en el presente trabajo, se definieron los siguientes objetivos de aprendizaje:

- Aprender a trabajar en grupo a partir de la autoevaluación y coevalucón.
- Conocer, comprender y aplicar en un caso concreto las herramientas de la mejora de la calidad: Diagrama de causa efecto, AMFE y QFD.

2.3 Estrategia didáctica

Trabajo Práctico Grupal.
Las estrategias didácticas desarrolladas se centraron dentro de dos Trabajos Prácticos Grupales, con un tiempo de 2 semanas para resolver cada uno. El primero abordaba los contenidos de las Herramientas de la Calidad, dadas por el Análisis de Modo y Efecto de Fallas (AMEF), Diagrama de Ishikawa, y el segundo la herramienta Análisis QFD o de Despliegue Funcional de la Calidad.

El curso fue divido, mediante la generación aleatoria de grupos de Moodle, en 4 grupos (A, B, C y D), quedando 10 integrantes en cada uno. La justificación de dicha división aleatoria se fundamenta en el interés por desarrollar la habilidad de trabajar en grupo con personas que no están acostumbrados/as a trabajar y que tal vez tengan otras metodologías y maneras de pensar. Situación potencial que vivirán próximamente en sus trabajos. Estos grupos se mantuvieron durante todo el cuatrimestre.

Consignas.

Para el primer trabajo practico, la cátedra preparó un caso a partir de un estudio real encontrado en la web. La estrategia del Estudio de Caso consiste en utilizar un caso real o adaptado como disparador y vehículo para abordar los contenidos deseados a través de un aprendizaje activo de los/as estudiantes y nutrido y enriquecido por la reflexión y el debate del trabajo en grupo. Es decir, el método de casos es una excelente oportunidad para trabajar en grupo, dando lugar a que discutan ideas, analicen distintos puntos de vistas, reflexionen sobre los nuevos contenidos y tal cual se enuncia en [12], lograr como resultado la construcción de una mayor tolerancia hacia las ideas de los demás, una disposición a escuchar las opiniones ajenas y un mayor confort cuando se trata de expresar un punto de vista. En el caso desarrollado para el primer trabajo práctico, se detallaban los procesos realizados en una industria láctea, desde el ingreso de la materia prima hasta la obtención del producto final. En base a dicha descripción, cada grupo debía realizar un AMEF (o FMEA por sus siglas en inglés), el cual es un procedimiento que permite identificar fallas en productos, procesos y sistemas, así como evaluar y clasificar de manera objetiva sus efectos, causas y elementos de identificación, para de esta forma, evitar su ocurrencia y tener un método documentado de prevención. Además de utilizar la información suministrada, si lo consideraban necesario, podían realizar alguna investigación extra del proceso. Dado que el proceso era muy extenso, a cada grupo se les asignó un conjunto de subprocesos, buscando equilibrar el trabajo a realizar.

Por otro lado, dentro del caso, se plantea una problemática puntual que demanda un análisis para determinar las posibles causas. Para ello, la segunda parte de la consigna especifica que deben realizar un Diagrama de Ishikawa (o también conocido como de Causa-Efecto o de Espina de pescado), cuya metodología sostiene que todo problema es originado por alguna de las macrocausas que plantea (Maquinaria, Métodos, Personas, Ambiente, Materiales y Mantenimiento), y estas deben ser analizadas y probadas, una a una, a fin de comprobar cuál de ellas está realmente causando el efecto (problema) que se quiere eliminar, y determinar así la causa puntual a abordar. La consigna aquí, consiste en realizar un Juego de Roles (*role playing*) es decir un juego de simulación que consiste principalmente en la representación de situaciones reales, donde cada participante debe actuar o defender un rol o papel, interactuando bajo determinadas reglas con el resto de los partícipes [14-15]. Según [16] los juegos de roles se caracterizan por demandar la toma de decisiones, y esto hace que estén orientados hacia el futuro, en tanto que dan la oportunidad al participante de tomar decisiones sobre problemas reales y observar las consecuencias más previsibles, así como de reorientar dichas decisiones en función de las retroalimentaciones recibidas. Entre los valores psicopedagógicos que aportan los juegos de simulación como estrategia metodológica, se destacan su potencialidad para repasar conocimientos y habilidades, desarrollar el aprendizaje existente y descubrir aspectos deducibles a partir de este y como elemento motivador [16-17]. Además, el juego de roles permite analizar los problemas relacionados con las relaciones humanas y fortalece la capacidad de la empatía [18]. Según [19] se mejora la experiencia educativa, ya que promueve el pensamiento crítico y las habilidades analíticas, el fomento de las competencias de comunicación oral y escrita, y el fomento de la confianza de los/las estudiantes [20].

Específicamente, en el Juego de Roles solicitado en el trabajo práctico, cada integrante del grupo debe tomar el rol de una de las personas del equipo de trabajo encargado de encontrar la causa del problema (Gerente de producción, Jefe/a de turno de producción, Responsable de mantenimiento electromecánico, Responsable del laboratorio, Responsable del control de calidad, Responsable de seguridad e higiene, Operador/a de higienización, Operador/a de planta, Operador/a del sector de envasado). Para ello, deben simular el proceso de analizar un problema para encontrar su causa mediante la metodología propuesta por Ishikawa. Brevemente, esta consiste en realizar una "tormenta de ideas" debatiendo sobre todas las causas que podrían originar el problema, y luego ir desagregando cada una, respondiendo a la pregunta ¿por qué? reiteradas veces, descartando algunas y seleccionando otras como causas principales. La causa final a seleccionar mediante el diseño del diagrama, la decidirá cada grupo, pero debe ocurrir dentro de alguno de los subprocesos asignados a cada equipo. Aprovechando el auge de las videollamadas, la simulación debía ser realizada en algún software/plataforma que permita su grabación, y esta sería parte de los archivos a entregar como resolución del Trabajo Práctico. Por otro lado, se aclaró que el video no debía durar más de 15 minutos y que cada participante debía especificar en el video que rol estaba desarrollando.

Para el segundo Trabajo Practico, también se planteó un caso armado por la cátedra, el cual expone la situación y desafíos de una empresa al diseñar su Plan Estratégico. En el mismo se muestran 3 archivos que contienen datos relevados de entrevistas a los clientes, un diagrama que sintetiza dichos datos y un cuadro de relación entre las necesidades del cliente y las necesidades de la empresa. Con toda esta información y las consideraciones que piensen pertinentes deben completar el cuadro característico del análisis QFD, y eso será el archivo que deben entregar para su calificación. Cabe aclarar que dicha resolución no está atada a una única respuesta correcta, sino que pueden darse diferentes matices dentro de un rango de lo que se considera como "bien resuelto", donde se contempla la coherencia integral del cuadro y los fundamentos dados en cada caso. Sin embargo, es de esperar que el producto final resultará más nutrido si se da un análisis integral desde el grupo, intercambiando ideas e interpretaciones de los detalles del caso planteado.

2.4 Evaluación

Pautas del trabajo en grupo y criterios de evaluación.

Antes de pasar a la presentación de las actividades se establecieron las pautas para el trabajo en grupo y se comentaron que al final de la actividad, realizarían una coevaluación y autoevaluación respecto al cumplimiento de dichas pautas. Se proyectaron las pautas establecidas por Wassermann [12] y se preguntó si deseaban sacar o agregar alguna más. Asimismo, se conversó brevemente sobre los posibles roles que podrían surgir dentro del grupo y la importancia de reconocerlos y tomar conciencia de su existencia como medio para el funcionamiento eficiente del grupo y la generación de sinergia.

A la par de la publicación de las consignas para el desarrollo de los trabajos prácticos, se comunicó el sistema de evaluación. Este estuvo dividido entre la evaluación que haría la cátedra, la autoevalución y la co-evaluación. Para la primera, los criterios de

evaluación fueron: Entrega en tiempo y forma completa, aplicación correcta de las metodologías AMFE, Causa-Efecto y QFD, fundamentaciones realizadas en cada caso, creatividad y resolución coherente y acorde. En base a estos se asigna una calificación dada por Aprobado, Aprobado con correcciones o Rehacer. Para las auto y co-evaluaciones en base a las pautas definidas en [12] se exponen los criterios de evaluación, las cuales se realizarán luego de entregar la resolución de las consignas. Los instrumentos utilizados se detallan en las siguientes secciones.

Instrumentos para la Auto y Co-Evaluación

Aprovechando la plataforma virtual *Moodle* a través de la cual se desarrolló la asignatura en el mencionado cuatrimestre, se utilizó el módulo "Taller" en el cual es posible la evaluación entre compañeros/as. En este, luego de cargado un trabajo, cada integrante del grupo tiene acceso a un cuestionario para autoevaluarse y evaluar a los demás integrantes del grupo. El mismo estuvo compuesto por una planilla y una pregunta abierta de retroalimentación general. Como se mencionó en la introducción, en esta experiencia se proponen instancias de autoevaluación y coevaluación para aprender y mejorar el trabajo en grupo. Es decir, las evaluaciones están centradas en el proceso de trabajo grupal y no en el producto final. Es por esto que los criterios de evaluación tienen que ver con el cumplimento de las pautas establecidas y el desarrollo de habilidades consideradas propicias para un buen y eficiente desenvolvimiento dentro de un grupo de personas. La planilla utilizada se muestra en la Tabla 1. En el espacio de retroalimentación general, se especificaba que el objetivo del mismo era que desarrollen un comentario sincero que signifique una crítica constructiva que pueda ayudar a la persona evaluada a mejorar su desempeño dentro de un trabajo en grupo. El espacio era el mismo en la coevaluación como en la autoevaluación. Una vez completado el cuestionario, se debe esperar a que todos/as los miembros del grupo completen esa fase, para que puedan visualizar las evaluaciones realizadas, las cuales se muestran de forma anónima. Asimismo, se calcula un promedio entre las calificaciones dadas y las recibidas. Si bien hay muchas variantes en este módulo, así fue como se utilizó en la cátedra.

Tabla 1. Planilla de autoevaluación y coevaluación

Criterio a evaluar / Indicadores	**Calificación asignada**			
	1	**2**	**3**	**4**
¿Respetó y consideró las ideas y opiniones de los demás?	Nunca	A veces	Generalmente	Siempre
Preparación y manejo de los contenidos al momento de desarrollar el trabajo:	Malo	Regular	Bueno	Muy bueno
Participación durante el desarrollo de la actividad	Malo	Regular	Bueno	Muy bueno
Focalización e iniciativa en el desarrollo del trabajo.	Malo	Regular	Bueno	Muy bueno
Grado de integración de los demás miembros del grupo (Considerar actitudes de cohesión	Bajo	Moderado	Medio	Alto

del grupo, interés por la opinión de los demás, iniciativas de integración a los/as compañeros excluidos por la razón que fuera, búsqueda de consensos, etc.)				

2.4.1 Encuesta final

Finalizado el periodo de clases y evaluaciones, se les pidió a los/as estudiantes que completen un formulario de Google, el cual pretendía generar un último análisis y reflexión del trabajo en grupo experimentado. El mismo recolectó información acerca de quién cumplió cada rol mayoritariamente dentro del grupo y qué rol sintieron personalmente que se desarrollaron mejor. Para ello se plantearon preguntas para que indiquen quien desarrolló cada uno de los roles, cuyas opciones de respuesta eran los integrantes del grupo. Basados en la clasificación de roles del texto de [21], y considerando la situación, contexto y experiencia a desarrollar, se indagó a cerca de: ¿Quién llevó el tiempo, agilizó el trabajo y focalizó en los momentos de dispersión? ¿Quién escribía las respuestas, transformando las repuestas habladas en respuestas escritas? ¿Quién moderaba la dinámica del grupo, haciendo participar a todos? ¿Quién buscaba información, aportando datos e ideas nuevas constantemente? ¿Quién evaluaba el cumplimiento de las consignas, realizando críticas constructivas en caso necesario? ¿Se desarrolló algún otro rol? ¿Quién lo hizo?

En esta encuesta también se pidió que indicaran en una escala del 1 al 5, donde 1 corresponde a “No me sirvió nada” y 5 “Me sirvió mucho”: ¿En qué medida consideras que las auto y coevaluaciones sirvieron para mejorar tu desempeño en el grupo? Y ¿En qué medida consideras que las auto y coevaluaciones sirvieron para mejorar el desempeño en el grupo de tus compañeros?

3 Resultados

A continuación, se publican los principales resultados obtenidos tanto del desarrollo en sí mismo de los trabajos prácticos como de los instrumentos de autoevaluación y evaluación entre pares, como se la encuesta final del curso. Los mismo son analizados cuantitativa y cualitativamente.

3.1 Evaluación del producto final

Como se mencionó anteriormente, la evaluación de los productos finales de cada trabajo práctico estuvo a cargo de la cátedra según los criterios establecidos. Para el primer trabajo práctico, dos grupos fueron calificados como Aprobados y los otros dos como Aprobados con Correcciones. En cada caso, se dio la devolución correspondiente a cada criterio de evaluación especificado. Con respecto a los videos de juego de roles entregados, se notó un gran compromiso y seriedad por parte de los y las estudiantes. Cabe aclarar, que en el juego de roles planteado no existía la instancia de evaluar las consecuencias de las decisiones tomadas, sino que, se apuntaba a analizar el proceso de la

toma de decisión. Lo cual pudo observarse muy bien en los videos entregados. Es decir, pude verse si realizaban un "brainstorming", si llegaban a una decisión o no, si la fundamentaban, si había un coordinador, entre otras cuestiones propias de la metodología Ishikawa

En el segundo trabajo práctico todas las calificaciones fueron de Aprobado, al cumplir con las especificaciones de la metodología QFD y los demás criterios de evaluación.

3.2 Cuestionarios de Autoevaluación y Coevaluación

En esta sección, se describen los resultados obtenidos en los cuestionarios de autoevaluación y coevaluación. En primer lugar, se hablar de los resultados de la planilla y luego del espacio de retroalimentación general.

Análisis de las planillas

Se analizaron todas las evaluaciones realizadas y para un análisis cuantitativo, se asignó un puntaje del 1 al 4 a las valorizaciones de la planilla, tal cual se muestra en la Tabla 1. De esta forma, se obtuvieron promedios y diferencias comparativas entre una instancia y la otra. Las mismas se muestran en la Tabla 2.

Tabla 2. Resultados promedios de las planillas de autoevaluación y coevaluación. Diferencias entre ellas y en cada instancia.

Grupo	Instancia	Promedio de calificaciones		Diferencias			Diferencias porcentuales		
		Autoevaluación	Otorgadas	O-A	Inst.2-Inst.1		O-A	Inst.2-Inst.1	
A	1	3.76	3.69	-0.07	-0.08	0.07	-1.90	-2.17	1.86
B		3.24	3.55	0.30	0.11	-0.21	8.54	3.31	-6.33
C		3.51	3.70	0.19	0.03	-0.15	5.02	0.81	-4.16
D		3.34	3.53	0.19	0.06	-0.04	5.26	1.68	-1.23
A	2	3.68	3.76	0.08			2.13		
B		3.36	3.34	-0.02			-0.58		
C		3.54	3.55	0.01			0.27		
D		3.40	3.49	0.09			2.46		

Las instancias 1 y 2 corresponden a las evaluaciones realizadas luego del primer y segundo trabajo práctico, respectivamente. Todos los grupos tienen un promedio entre 3 y 4 puntos, registrándose el menor puntaje de auto evaluación en el Grupo B (3.24) y el mayor en el Grupo A (3.76), ambos en la instancia 1. Para el caso de las calificaciones otorgadas promedio, la menor se ubica en el Grupo B (3.34) y la mayor en el Grupo A (3.76), ambos de la segunda instancia. Por otro lado, se observa que fueron mayoritariamente más autocríticos que críticos con sus compañeros ya que la diferencia entre calificaciones Otorgadas y Autoasignadas (columnas O-A) es positiva en casi todos los casos. También se realiza la comparación entre las evaluaciones de la primera instancia

versus la segunda y se destaca que las autoevaluaciones mejoraron y las otorgadas empeoraron. Separando las calificaciones, sólo el 1.3% de las evaluaciones corresponden a calificaciones de 1 o 2 puntos.

Posteriormente se calcularon los promedios de las calificaciones asignadas según cada uno de los criterios de la planilla, por cada uno de los grupos en cada instancia y el total. Si bien todos los promedios se observan entre los 3 y 4 puntos, se ve que el criterio que recibió las calificaciones más bajas fue C2: "Preparación y manejo de los contenidos al momento de desarrollar el trabajo". Mientras que la característica más valorada fue C1: "Respetó y consideró las ideas y opiniones de los demás". Estos resultados nos invitan a pensar que, durante el desarrollo del trabajo, los/as estudiantes le dieron mayor ponderación a aspectos grupales como el cumplimiento de las pautas establecidas, que a cuestiones individuales como lo es la preparación necesaria para abordar las consignas. Asimismo, en el gráfico de la Figura 1 se puede ver como varían las valoraciones de cada criterio de instancia a instancia y entre los grupos.

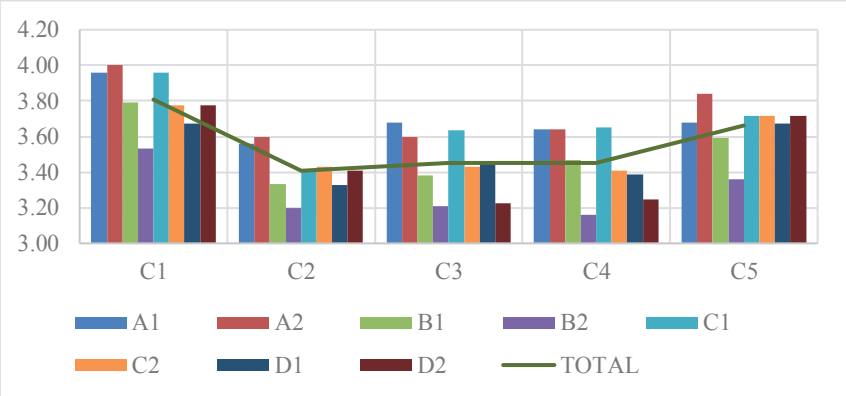

Fig. 1. Puntuaciones promedio por criterio de evaluación según cada grupo y en cada instancia. C1: "Respetó y consideró las ideas y opiniones de los demás"; C2: "Preparación y manejo de los contenidos al momento de desarrollar el trabajo"; C3: "Participación durante el desarrollo de la actividad"; C4: "Focalización e iniciativa en el desarrollo del trabajo."; C5: "Grado de integración de los demás miembros del grupo"

Análisis de los espacios de retroalimentación

Se explican a continuación los resultados obtenidos del análisis de las respuestas dadas en el espacio de retroalimentación. Primero se publican los establecidos en la coevaluación y luego en la autoevaluación.

Espacio de Retroalimentación en la coevalución

Se leyeron todas las respuestas que dejaron los/as estudiantes a sus compañeros en el espacio de "retroalimentación general" y se las clasificó según la orientación y según la intención. La orientación se refiere a quién es el sujeto de evaluación de lo escrito y se diferenciaron: retroalimentación particular, a las que daban un comentario que demostraba que era particular hacia esa persona que estaban evaluando; retroalimentación

general, los comentarios que no demostraban ser personales del/la compañero/a evaluado/a, sino que era general hacia el grupo o incluso los que se repetían de un/a mismo/a evaluador/a a todos/as sus evaluados/as; y retroalimentación vacía (Respuestas en blanco). Por otro lado, la intención de la retroalimentación significa cuál es el objetivo que persigue la misma. Estas pueden ser Evaluativas o Descriptivas. Dentro de las primeras encontramos elogios y enaltecimientos por realizar bien un rol o tarea y, por otro lado, críticas constructivas o recomendaciones. Las descriptivas se caracterizan por comentarios varios sin juzgar ni elogiar, o que indican qué rol ocupó en el grupo. En la Tabla 3 se muestran la contabilización de cada uno según cada grupo e instancia. En los Gráficos 2 y 3 se observa como la mayoría se trataron de retroalimentaciones particulares y de elogios, y resultó sumamente parejo entre las otras 2 categorías. Estos datos dan pie a concluir que han aprovechado los espacios de coevaluación, dedicándole tiempo y reflexión a esa tarea e inclusive dando recomendaciones o críticas constructivas a sus compañeros/as.

Tabla 3. Cantidad de tipo de retroalimentaciones según Orientación y según Intención

Grupo. Instancia	Orientación			Intención		
	Particular	General	Vacío	Elogio	Comentario	Crítica constructiva
A1	16	4	0	19	3	2
A2	9	7	4	20	0	0
B1	59	3	10	56	7	15
B2	35	14	23	31	8	12
C1	17	18	7	40	8	8
C2	10	26	6	39	2	1
D1	22	2	18	28	4	4
D2	18	6	18	25	2	1

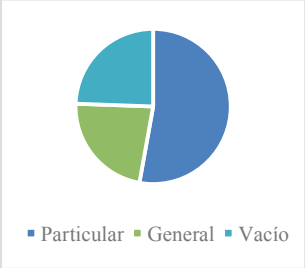

Fig. 2. Distribución de las retroalimentaciones según su orientación.

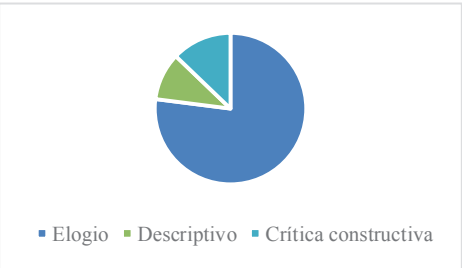

Fig. 3. Distribución de las retroalimentaciones según su intención

Espacio de retroalimentación en la autoevaluación

Del espacio de retroalimentación general de la autoevaluación, pudieron obtenerse conclusiones cualitativas respecto al funcionamiento interno de cada equipo. Es decir, en la reflexión interna que cada integrante realizó, pudieron reflejarse las situaciones particulares vividas en el equipo. Las mismas se enuncian a continuación para cada grupo:

Grupo A: Les costó encontrarse al principio, pero luego funcionó muy bien, sus integrantes se sintieron cómodos y hubo buena sinergia de grupo.

Grupo B: El funcionamiento respecto a la consigna aparenta haber sido bueno. Hay muchas reflexiones respecto a la importancia de la paciencia y la escucha de las opiniones de los demás, resaltando lo fundamental de dichas actitudes para una buena sinergia de grupo. En la segunda instancia, se destacan muchos comentarios respecto a la dificultad para coordinar el trabajo y hasta parece haber sido resuelta la consigna solo por una parte del grupo, con la no participación de algunos/as. Es interesante destacar que estas complicaciones dentro del grupo no se reflejan en las valorizaciones de la planilla (como puede verse en la Tabla 2, el promedio del Grupo B en el segundo trabajo práctico es de 3,36 puntos en la autoevaluación y 3,34 en la coevaluación), más bien son encontradas como comentarios en el espacio de retroalimentación.

Grupo C: El grupo afirma un muy buen funcionamiento, con desafíos a la hora de organizarse, pero luego logrando que sus integrantes se sintieran cómodos y resulte en una buena experiencia de trabajo.

Grupo D: Buen funcionamiento del grupo. Se destacan varias reflexiones respecto a la novedad de la experiencia de trabajar con personas desconocidas y de lo fortalecedor de la experiencia que les permitió poner a prueba timidez, opiniones de otros, organización virtual y comunicación en general.

Por otro lado, se sabe que trabajar en equipo supone el desarrollo de diversas capacidades como pueden ser: la habilidad para comunicar, un grado de conocimiento de uno mismo, la posibilidad de reflexionar y tomar distancia de las situaciones en que se inserta, tolerar la incertidumbre, saber escuchar, pensar que el otro puede aportar una idea, que no conocía, tener confianza en los otros, ser capaz de dialogar, intercambiar ideas y construir desde el consenso. La reflexión sobre el desarrollo de dichas capacidades ha quedado en evidencia en los espacios de retroalimentación de las autoevalauciones. Por ejemplo, el reconocimiento de las limitaciones o desafíos propios se expresan en comentarios como “Considero que me cuesta dar la iniciativa, pero una vez que se plantea el trabajo sigo el ritmo de mis compañeros, coordinando con ellos la realización y distribución de tareas”; “Creo que debo trabajar en fomentar la integración grupal y la distribución de tareas, y tratar de considerar opiniones”.

El saber escuchar y pensar que el otro o la otra puede aportar una idea se ve muy bien reflejado en las siguientes frases: “Trabajar de manera colaborativa con ellos me sirvió para confiar en que cada uno es capaz de cumplir con su parte, además pude trabajar la paciencia” ; “Mediar ideas enriquece de manera positiva gracias a los diferentes puntos de vista de cada integrante”; “Entendí que se puede trabajar en grupo, pero es de suma importancia la actitud de cada integrante, y es muy importante saber compartir y delegar responsabilidades”.

La autoestima en un grado adecuado es también una capacidad deseable en los integrantes de un grupo. En algunas frases se descubre como la autoestima ha sido reforzada gracias al trabajo en grupo realizado, como en "He logrado relacionarme de manera excelente con compañeros que no conocía" y "El trabajo en equipo fue muy bueno, hemos estado de acuerdo en las formas de su realización y todos hemos aportado dentro de nuestras posibilidades".

Por otro lado, los/as estudiantes también reconocen momentos de dificultad atravesados en el trabajo grupal. Esto puede considerarse natural porque no debemos olvidar que no todos/as los alumnos/as se inclinan con gusto hacia la participación en el trabajo en grupo. Básicamente, puede deberse a que no tienen intención de compartir sus ideas, esfuerzos y el resultado de su trabajo con otros/as, porque se resisten a colaborar en una producción que no les habrá de pertenecer en exclusividad. En algunos casos, se trata de personas con fuertes objetivos personales y en otros por considerar los trabajos grupales como una pérdida de tiempo, considerándose capaces de hacer solos la actividad indicada sin necesidad de reunirse con otros/as [22]. A esto puede sumarse la desconfianza creada en experiencias previas. Revisando las reflexiones, se encuentran las siguientes frases sustentando dichas dificultades: "Si bien participo y me esfuerzo mucho en la realización de los trabajos, haciendo las actividades como estudiando el material de lectura, creo que debo mejorar en el trabajo en grupo. Estar abierto a las opiniones de los demás y no solamente respetarlas, puesto que éstas son valiosas principalmente cuando nos interpelan". Por otro lado, conectando con la dificultad descripta previamente en el Grupo B, una de las personas integrantes expresa: "En un grupo hay integrantes que solo quieren hacer presencia, otros que quieren hacer cosas pero esperan que les digan que hacer y están los que directamente hacen y estos últimos perjudican a las demás en el sentido que no les dejan participar, integrarse, porque no entienden que trabajar en grupo es aceptar al otro, organizarse y preocuparse para que como grupo se avance sobre el tema. No se puede aprender bien el tema así de esta manera grupal y no me gusto esta modalidad que adoptan algunos integrantes". En este sentido, como sostienen Romero & Saune [21], el conflicto no solo es inherente al grupo sino que también es fundamental como motor de cambio, y consecuentemente, el proceso de resolución del conflicto es un proceso esencial de la dinámica grupal. Si este fuera un grupo que debiera perdurar por un mayor lapso de tiempo que el trabajado en este curso de 4 meses, indefectiblemente sus integrantes deberían evaluar sus actitudes para lograr un cambio que resuelva el conflicto existente.

Otra dificultad encontrada, fue la falta de preparación a las reuniones de trabajo: "Un aspecto a mejorar podría ser el funcionamiento de los encuentros, ya que en ocasiones experimentamos falta de ideas o trabas, momentos en los que nos encontrábamos todos conectados, pero tardábamos en encontrar una manera de resolverlo. Se entiende la importancia de haber leído previamente todo el material y de haber pensado algunas ideas o contribuciones para que el encuentro sea ágil y no se tenga que recurrir a la bibliografía por desconocimiento". Este comentario representa muchos otros que expresaban la misma idea respecto a la importancia de prepararse e interiorizarse respecto a la consigna y la temática previo al encuentro del grupo, para poder trabajar más ágilmente.

Además, está en línea con lo mencionado previamente en el análisis cuantitativo, referido a que el criterio de evaluación C2: "Preparación y manejo de los contenidos al momento de desarrollar el trabajo" haya recibido la menor valoración promedio.

Por último, como se mencionó previamente, la reflexión es una capacidad sumamente importante para la mejora del desempeño dentro de un grupo. Esto queda bien explicado en el siguiente comentario: "La posibilidad de reflexionar acerca del trabajo realizado ayuda a poner en palabra cuestiones a considerar su importancia y otras a revisarlas para poder aprender formas de mejorar. No es usual que tengamos espacios así en trabajos grupales. Es importante reflexionar sobre las prácticas realizadas para hacerlas más efectivas. Si uno no reflexiona lo que hace, generalmente lo repite mecánicamente sin ningún cambio y pierde la oportunidad de mejora."

3.3 Análisis de la encuesta final

A continuación, se exponen los resultados obtenidos de la encuesta realizada al final del curso. En primera instancia se describe como fueron valorados los cuestionarios de auto y coevaluación, y luego exponen los resultados y reflexiones respecto a la distribución de roles dentro de los grupos.

Valorización del cuestionario

Como se describió en la sección de Instrumentos, en la encuesta dada al final del cursado se les pidió que respondan a dos preguntas considerando una escala del 1 al 5, donde 1 corresponde a "No me sirvió nada" y 5 "Me sirvió mucho". Dichas preguntas y el promedio de sus respuestas se muestran en la Tabla 4.

Tabla 4. Promedios obtenidos en la valorización de los cuestionarios de auto y coevaluación, en la encuesta final del curso.

Grupos	¿En qué medida consideras que las auto y coevaluaciones sirvieron para mejorar tu desempeño en el grupo?	¿En qué medida consideras que las auto y coevaluaciones sirvieron para mejorar del desempeño en el grupo de tus compañeros?
A	1.40	1.40
B	3.67	2.56
C	3.17	3.17
D	4.00	3.60
Promedio	3.06	2.68

Puede verse que los grupos B, C y D consideran que las auto y coevaluaciones sirvieron en buena medida (mayor a 3 puntos) al mejoramiento del desempeño personal en el trabajo en grupo, y exceptuando el Grupo B, también contribuyeron a la mejora del trabajo de los compañeros.

La segunda pregunta tenía como objetivo principal analizar si el hecho de calificar a los compañeros según sus actitudes en un grupo representaría una manera de expresar sus disconformidades o deseos en caso de que el desempeño del grupo no sea bueno,

esperando así, que la persona cambie su actitud. En base a las respuestas dadas en la planilla, en muy pocos casos se registraron comentarios que indiquen que algún integrante del grupo no estaba trabajando de la manera esperada (1,3% como se dijo anteriormente). Sin embargo, observando las retroalimentaciones, en muchos casos sí se hacía referencia a dichas situaciones, pero normalmente se justificaba y se demostraba empatía con el/la compañero/a con comentarios como "no participó mucho, pero entiendo que no ha podido por sus exigencias laborales y familiares".

Observando y comparando los valores promedios de cada pregunta, se concluye que en general, el cuestionario contribuyó más a la mejora del propio desempeño (3.06 puntos) que el percibido en los compañeros/as (2.68 puntos).

Distribución de Roles

En esta última encuesta, también se indagó acerca de la distribución de roles dentro de cada grupo. Específicamente se preguntó quién consideraba que había desarrollado cada uno de los roles mencionados al principio, teniendo la opción de tildar a más de un/a compañero/a, además de la opción "TODOS/AS" y "NADIE". Los principales resultados que se obtienen de esta sección tienen que ver con las muchas diferencias de percepciones ocurridas. A continuación se detallan algunos ejemplos:

- Un mismo rol era tildado por algunos integrantes como que fue desarrollado por TODOS/AS, mientras que otros integrantes tildaban la opción de NADIE. Sucedió en el rol de *Moderador de la dinámica grupal* y en el de *Evaluar el cumplimiento de las consignas*. Seguramente esta controversia pueda deberse a una interpretación distinta en cada caso. Por ejemplo, la persona que señaló la opción de NADIE pudo haber querido decir que nadie específicamente cumplió ese rol, es decir, que todos/as lo hicieron a su manera y tiempo, por lo que así, podría suponerse que hay coincidencia en la respuesta TODOS/AS.
- La gran mayoría del grupo atribuyó un rol a una persona y esa persona no se lo atribuyó.
- No hubo ni un caso en donde todas las respuestas coincidieran.

Otra pregunta de dicha sección fue si consideraban que se había desarrollado algún otro rol además de los especificados. La mayoría de las respuestas fueron NO, mientras que algunas de las respuestas no respondían al concepto de rol o se encontraban dentro de alguno de los roles ya establecidos. Los roles que podrían considerarse adicionales son:

- Persona intermediaria con las docentes: Quién hacia las preguntas cuando surgían dudas específicas de las consignas.
- Persona que facilitó las cuestiones técnicas: quien se grabó las clases de la materia, quien edito el video, programaba las reuniones virtuales, etc.

Asimismo, se preguntó cuál era el rol que consideraba personalmente que mejor y más había desarrollado en el grupo, dando como opciones los roles establecidos inicialmente y la opción libre "otro" para que expliquen cual. A continuación, se muestran las

respuestas de cada grupo, y la general que incluye todas las respuestas, en el conjunto de gráficos de la Figura 4. Se observa como en todos los grupos predominaron las personas que se identificaron mejor con el rol de buscar información y aportar nuevas ideas (color verde). En segundo lugar, se destaca el rol de evaluar el cumplimiento de las consignas y realizar críticas constructivas al trabajo realizado (color azul). Solamente en un grupo se reconocieron personas como moderadoras de la dinámica del grupo (Grupo A) y personas encargadas de escribir las respuestas y pasarlas en limpio (Grupo D).

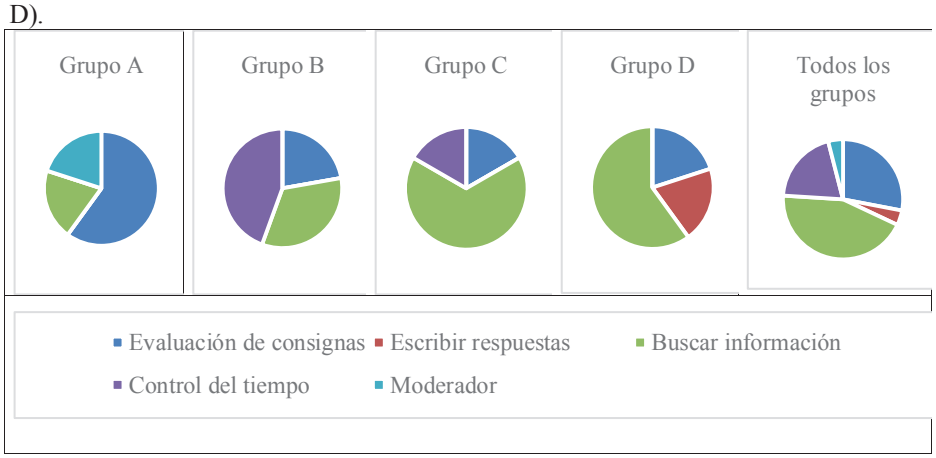

Fig. 4. Roles que los integrantes consideraron personalmente que mejor y más habían desarrollado en el grupo

4 Conclusiones y trabajos futuros

En el presente trabajo se detalló un procedimiento para alcanzar el objetivo de aprendizaje de aprender a trabajar en grupo, habilidad y competencia crecientemente demandada en el mundo laboral, principalmente en Ingeniería. La propuesta se basó en generar instrumentos y espacios para la autoevaluación y evaluación entre pares, dentro del trabajo grupal. La misma se desarrollado en un curso específico, en contexto COVID-19, pero puede ser perfectamente replicable y adaptable a cualquier otra clase. Partiendo de la generación de grupos aleatorios, consensuando las pautas de trabajo dentro de los grupos, estableciendo los criterios de evaluación de la cátedra, de auto y coevaluación y proporcionando para ello, instrumentos de muy sencillo uso, pudieron generarse instancias de importantes reflexiones tanto para los integrantes de cada grupo como para la cátedra docente.

Sabemos que uno de los objetivos de la educación superior es generar competencias en los estudiantes para el desarrollo profesional. Sin embargo, algunos autores sostienen que las competencias solo se adquieren en la práctica y por ello la controversia de la posibilidad o no del egreso de personas competentes, principalmente, porque trabajar en entornos reales no siempre es posible. Igualmente, la educación universitaria puede proporcionar a los/las estudiantes experiencias cercanas a la realidad para aprender a enfrentar los desafíos que se viven en los entornos reales, a través de herramientas como

el estudio de casos y el juego de roles. Estas fueron utilizadas por la cátedra persiguiendo el objetivo de acercar a los/las alumnos/as a situaciones posibles y potenciales de sus futuros entornos laborales, a la vez de que son herramientas que ajustan muy bien con la modalidad virtual y el proceso de enseñanza aprendizaje.

Si bien el promedio de las calificaciones de todos los criterios, tanto de las autoevaluaciones como de las coevaluaciones, fueron buenas o muy buenas, el espacio de devolución y retroalimentación fue aprovechado, dedicándole tiempo y reflexión a esa tarea e inclusive dando recomendaciones o críticas constructivas a sus compañeros/as. De hecho, en un grupo, una de las instancias de trabajo parece haber sido resuelta por solo una parte del grupo, es decir, no hubo una participación completa de todos sus miembros, pero sin embargo, esto no se refleja en las calificaciones de la planilla de co-evaluación, sino que aparece como autocrítica de parte de algunas personas o como comentario de retroalimentación entre pares. Esto nos invita a pensar acerca de que, si bien las coevaluaciones no significaban una ponderación directa en la nota final del curso, es decir, no se trataba de una evaluación sumativa sino formativa, igualmente los y las estudiantes lo vivieron como una instancia de calificación, con prudencia a la hora de marcar un error o una actitud no favorable para el grupo. Es decir, considerando al error como una falla y no como una oportunidad de mejora y aprendizaje. En experiencias futuras, consideramos que es importante trabajar con los/as estudiantes, los distintos conceptos de error, procurando generar pensamientos que reconstruyan la mala fama que dicho concepto tiene asociada.

Por otro lado, en este trabajo quedó en evidencia la importancia de generar espacios de reflexión y autoevaluación en los y las estudiantes, como medio para el desarrollo de habilidades de conocimiento propio, reconociéndose como sujetos dentro de un grupo, con virtudes y debilidades que significan oportunidades de mejora.

Por último, del análisis de la sección de distribución de roles de la encuesta se desprenden dos conclusiones importantes:

- En futuras experiencias debe reforzarse el significado de rol dentro de un grupo, para mejorar la lectura del desarrollo o no de los mismos. El hecho de que nadie se haya autoreconocido en otro rol fuera de los establecidos inicialmente, y que sí los hayan propuesto para otros miembros del grupo, sumado a la gran variedad de respuestas en las asignaciones, indicaría que les resultó más fácil detectar el rol que desarrolló uno/a mismo/a que el que desarrolló un/a compañero/a.
- Que no se haya identificado cada rol con una persona unánimemente habla de que los grupos no alcanzaron a consolidarse. Como se dijo en la introducción, un grupo no es solo un conjunto de personas, sino que debe existir una trama vincular y una historia compartida, fundada en base a un objetivo en común. En este caso, podría hablarse de que hubo *grupalidad*, un conjunto de personas con la potencialidad de convertirse en grupo [23].

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Modelo matemático para evaluación adaptativa

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Abstract. Para medir el conocimiento adquirido por un estudiante sobre un conjunto de objetivo de aprendizaje dado, es necesario realizar una evaluación. En general, en los colegios se utilizan pruebas estandarizadas para realizar esto. Sin embargo, este tipo de evaluaciones no logra captar el real conocimiento de los estudiantes sobre un conjunto de objetivos de aprendizajes determinado. En el presente trabajo se propone un nuevo método para realizar test que se adapten a los conocimientos de los estudiantes. Para ello, se consideran la relación entre los distintos objetivos de aprendizaje y la información histórica de un banco de preguntas.

Keywords: test adaptativo, modelo matemático, educación

1 Introducción

Actualmente existe una diversidad de aplicaciones o páginas (e.g., Duolingo, Coursera) que dictan cursos de diversas materias. Para evaluar a los usuarios, en general, utilizan test que se adaptan al nivel de conocimiento de ellos. Para realizar esto, en general, utilizan la información de evaluaciones previas para saber que preguntas asignar.

En términos pedagógicos cada unidad académica posee un conjunto de ejes de aprendizajes (e.g., operaciones matemáticas) y cada eje contiene un conjunto de objetivos de aprendizajes (eg., suma, multiplicación, potencias) que dependen del nivel que se esté cursando. Teóricamente existe una relación entre cada objetivo de aprendizaje. Por ejemplo, para saber multiplicar se debe saber anteriormente sumar y a su vez multiplicar se debe saber antes de las potencias. De este modo podemos definir, para cada objetivo de aprendizaje, un conjunto de objetivos de aprendizajes antecesores y sucesores.

Si bien este tipo de aplicaciones han proliferado en los últimos años, aún no se incorporan dichas tecnologías a los colegios. Tanto como para los administradores de los colegios como los profesores es importante tener conocimiento del aprendizaje obtenido por los estudiantes. Por un lado, a los educadores les permite conocer los niveles de conocimiento de sus estudiantes y con ello buscar las mejores estrategias para continuar con sus clases, y por otro lado les sirve a los administradores para evaluar el desempeño de sus profesores.

En general, para cumplir con esto se realizan evaluaciones periódicamente para saber si los estudiantes han aprendido la materia estudiada. Sin embargo,

muchas veces estas pruebas son estandarizadas, no logrando describir realmente los conocimientos de cada estudiante. Por esta razón, actualmente los educadores buscan nuevas metodologías de evaluación. Entre estas se encuentran los llamados test adaptativos los cuales van realizando preguntas considerando las respuestas previas del estudiante. Este tipo de test permite conocer de mejor manera el real nivel de conocimiento adquirido por cada estudiante. Por ejemplo, podemos permitir que el test considere objetivos de aprendizajes previos del conjunto considerado, de tal manera de determinar los objetivos aprendizajes antecesores que no ha alcanzado a adquirir un estudiante con mal rendimiento.

En el presente trabajo presentamos un nuevo método para desarrollar test adaptativos dirigido especialmente a colegios. El método consiste en tres etapas: primero construir un índice que permita relacionar los diferentes objetivos de aprendizaje, segundo construir un grafo de relación entre objetivos de aprendizaje y tercero construir grafo entre un banco de preguntas y los objetivos de aprendizaje, el cual se utilizará como input para el test adaptativo.

2 Definición del problema

Considere la materia de matemática. Sea $\mathcal{T}$ el conjunto de tipo de enseñanza (e.g., primaria, secundaria). Para cada tipo de enseñanza $t \in \mathcal{T}$ existe un conjunto de niveles $\mathcal{N}_t$. Cada dupla de tipo de enseñanza, nivel (t, n), $t \in \mathcal{T}, n \in \mathcal{N}_t$ existe asociado un conjunto de unidades $\mathcal{U}_{t,n}$, donde cada unidad $u \in \mathcal{U}_{t,n}$ tiene un conjunto de objetivos de aprendizaje $\mathcal{O}_u$. Asimismo, cada objetivo de aprendizaje $o \in \mathcal{O}_{t,n}$ tiene un único eje de aprendizaje.

Sea $\mathcal{P}_y$ el conjunto de preguntas confeccionada en el año y. Cada pregunta $p \in \bigcup_y \mathcal{P}_y$ aborda un único objetivo de aprendizaje o^p. Se asume que cada pregunta presenta un valor de "dificultad" de valor f^p.

Considere que se sabe teóricamente que cada objetivo de aprendizaje $o \in \bigcup_{t,n} \mathcal{O}_{t,n}$ posee un conjunto de objetivos de aprendizaje predecesores $\mathcal{B}_o$ y un conjunto de objetivos de aprendizaje sucesores $\mathcal{A}_o$. Sea $\mathcal{P}_y^o$ el conjunto de preguntas confeccionada en el año y que abordan el objetivo o.

Por conveniencia, se denota $p(1)$ si la respuesta la pregunta p es correcta y $p(0)$ otro caso. Asuma que existe una gran cantidad de datos disponibles, tal que, es posible estimar la probabilidad condicionada $\Pr(p(1)|p'(1))$ -esto es la probabilidad de contestar bien la pregunta p dado que contesto bien la pregunta p', donde $p \in \bigcup_y \mathcal{P}_y^o$ y $p' \in \bigcup_y \mathcal{P}_y^{o'}$ con $o' \in \mathcal{B}_o$.

El problema del diseño de una evaluación adaptiva desde un banco de preguntas se define como sigue. Considere un conjunto de estudiantes $\mathcal{S}$, un conjunto de preguntas $\bigcup_y \mathcal{P}_y$ que abordan un conjunto de objetivo de aprendizaje $\bigcup_{t,n} \mathcal{O}_{t,n}$. Dado un estudiante $s \in S$ y un objetivo específico o, se desea determinar el conocimiento de los objetivos de aprendizaje en matemáticas por parte de un estudiante $s \in S$ a través un subconjunto de preguntas J_s de cardinalidad mínima.

3 Método inteligente y aplicación para la generación del test adaptativo

En esta sección se formula un método inteligente que permita la generación del test adaptativo. Este método basado en un modelo matemático el cual asume el análisis y el precálculo de: 1) la correlación entre las preguntas según los datos históricos disponibles del desempeño para un conjunto de estudiantes, 2) un grafo parcial de las relaciones entre los objetivos de aprendizaje, y 3) la estimación de la dificultad de la pregunta dentro del conjunto de preguntas que abordan el mismo objetivo según una métrica establecida por algún método psicométrico.

Nuestro método adopta la teoría de espacio del conocimiento [3, 5], buscando determinar las relaciones entre todas las preguntas considerando que cada pregunta aborda un objetivo de aprendizaje específico el cual posee *a priori* un conjunto de objetivos de aprendizaje sucesores y predecesores, maximizando la suma de las correlaciones obtenida por las selección de las relaciones determinadas entre preguntas.

Para ello, presentamos dos modelos matemáticos que ayudan a determinar dichas relaciones. Primero realizamos un modelo que relaciona objetivos de aprendizaje con objetivos de aprendizaje, el cual determian el conjunto de sucesores y antecesores de cada objetivo de aprendizaje. El segundo, determina la relación entre preguntas y objetivos de aprendizaje de este modo una pregunta $p \in o$ es asociada a un $o' \in \mathcal{B}_o \cup \mathcal{S}_o$.

3.1 Modelo pregunta-objetvo

Consideremos que el estudiante se encuentra en la pregunta $p \in \mathcal{P}_y$ que aborda el objetivo de aprendizaje $o^{\mathcal{P}}$. Si el estudiante responde correctamente, se continuará evaluando otro objetivo de aprendizaje que se encuentre dentro de los sucesores del objetivo de aprendizaje $o^{\mathcal{P}}$. Entonces se le asignará una pregunta $p^{'}$ correspondiente a un objetivo aprendizaje $o^{'} \in \mathcal{S}_o$. En caso que responda incorrectamente, se evaluará un objetivo que pertenzca al conjunto de predecesores $\wr$. Entonces, se le asignará una pregunta $p^{'} \in \mathcal{B}_o$). El siguiente modelo construye un grafo entre preguntas y objetivos de aprendizaje. La idea es que cada pregunta se conecte con un objetivo de aprendizaje perteneciente a los sucesores del objetivo de aprendizaje de la pregunta, y con un objetivo de aprendizaje perteneciente a los predecesores del objetivo de aprendizaje actual. Dicha conexión se realizará siempre y cuando la pregunta p tenga una correlación mayor a un paramétro K con las preguntas pertenecientes al objetivo de aprendizaje $o^{'} \in \mathcal{S}_o$. Para ello, definimos una variable binaria $x_{p,o'}$ que será 1 si la pregunta $p \in \mathcal{P}_y$ que aborda el objetivo de aprendeizaje $o^{\mathcal{P}}$ se une con el objetivo de aprendizaje $o^{'} \in \mathcal{S}_o \cup \mathcal{B}_o$. Por comodidad definimos $w_{pp'} = \sum_{p \in \cup_y \mathcal{P}_y^o} \sum_{p' \in \cup_y \mathcal{P}_y^{o'}} \Pr(p(1)|p'(1))/|\mathcal{P}_y^o|$.

$$\max \quad \sum_{o \in OA} \sum_{p \in \mathcal{P}_o} \sum_{o' \in \mathcal{B}_o \cup \mathcal{S}_o} x_{po'} w_{pp'} \tag{1}$$

$$\text{s.a.} \quad \sum_{o' \in \mathcal{B}_o} x_{po'} \leq 1 \qquad p \in \mathcal{P}_o, o \in OA \tag{2}$$

$$\sum_{o' \in \mathcal{S}_o} x_{po'} \leq 1 \qquad p \in \mathcal{P}_o, o \in OA \tag{3}$$
$$\sum_{o' \in \mathcal{S}_o} x_{po'} w_{pp'} \geq K \qquad p \in \mathcal{P}_o, o \in OA \tag{4}$$
$$\sum_{o' \in \mathcal{B}_o} x_{po'} w_{pp'} \geq K \qquad p \in \mathcal{P}_o, o \in OA \tag{5}$$
$$w_{po'} \geq \sum_{o'' \in \mathcal{S}_o} w_{po''} x_{po''} \qquad o \in OA, o^{'} \in \mathcal{S}_o, p \in \mathcal{P}_o \tag{6}$$
$$x_{po'} \in \{0,1\} \qquad o \in OA, p \in o, o' \in B(o) \cup S(o) \tag{7}$$

La restricción (2) y (4) asignan a lo más un predecesor y un sucesor a cada pregunta $p \in o$. En tanto la restricción (4) y (2) permiten que exista arista entre una pregunta p y un $o \in \mathcal{B}_o$ y un $o \in \mathcal{S}_o$ siempre y cuando la suma de $w_{pp'}$ sea mayor al umbral K.

3.2 Modelo objetivo-objetivo

Existe una sucesión de objetivo de aprendizaje que es dada por expertos. Con los datos históricos podemos chequear, si esta sucesión es correcta; o si las preguntas estan correctamente etiquetadas. Para ello, desarrollamos un modelo de programación matemática que establece las sucesiones (o caminos) de aprendizaje dada la respuestas de los estudiantes en las pruebas anteriores. El modelo sigue la misma lógica anterior. Si dos objetivos tienen una correlación mayor a un paramétro L dado y esta es la mayor entre todas las alterntivas se hace la conexión. Ahora bien, la medida de correlación la asumiremos como un operador $T(P_o, P_{o'})$.

$$\max \qquad \sum_{o \in OA} \sum_{o' \in OA \setminus \{o\}} y_{oo'} T(P_o, P_{o'}) \tag{8}$$
$$\text{s.a.} \qquad \sum_{o' \in OA \setminus \{o\}} y_{o'o} \leq 1 \qquad o \in OA \tag{9}$$
$$\sum_{o' \in OA \setminus \{o\}} y_{oo'} \leq 1 \qquad o \in OA \tag{10}$$
$$\sum_{o' \in OA \setminus \{o\}} y_{oo'} T(P_o, P_{o'}) \geq L \qquad o \in OA \tag{11}$$
$$\sum_{o' \in OA \setminus \{o\}} y_{oo'} T(P_o, P_{o'}) \geq L \qquad o \in OA \tag{12}$$
$$y_{oo'} \in \{0,1\} \qquad o \in OA, o' \in B(o) \cup S(o) \tag{13}$$

La resolución de estos modelos matemáticos puede ser llevada a cabo a través del uso de métodos de optimización combinatoria Inicialmente se adopta un enfoque basado en un algoritmo exacto y heurístico que permite la resolución del problema [4]. Para calibrar y estudiar la eficiencia del modelo se desarrolló un simulador de test que utiliza la información histórica de pruebas anteriores. Los resultados muestran, que el método se puede adaptar a diferentes diseños de test; segundo, que se puede obtener mayor información de los conocimientos de los estudiantes con test que se adapten a cada estudiante. Finalmente, el propósito del método presentado, es servir como herramienta para profesores y directores de establecimiento que faciliten el desarrollo de nuevas estrategias pedagógica adaptadas al conocimiento de cada estudiante.

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Optimización por Colonia de Hormigas para el Ruteo del Picking en Almacenes de Múltiples Bloques

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Abstract. Este artículo tiene como objetivo minimizar la distancia total recorrida para el problema del ruteo del picking (PRP), considerando almacenes 2D de múltiples bloques. Para esto, se formulan las distancias mínimas entre cada par de posiciones de almacenamiento a visitar en un tour, y se propone un algoritmo de optimización por colonia de hormigas (ACO), al cual se le realiza un ajuste de parámetros para garantizar un mejor desempeño para solucionar el PRP. Con base en experimentos computacionales, se establece que el ACO propuesto brinda soluciones de alta calidad y genera ahorros satisfactorios frente a una metaheurística y dos heurísticas ampliamente utilizadas para el PRP, requiriendo tiempos de computación viables para ambientes de simulación y ambientes de operación real de almacenes y centros de distribución.

Palabras clave: Preparación de Pedidos, ACO, Ruteo del Picking, Almacenes Multibloque, Metaheurísticas

1 Introducción

Los almacenes y centros de distribución (CEDIS) son componentes esenciales para la gestión de la cadena de suministro y la logística debido a que afectan significativamente el servicio al cliente, los costos y la eficiencia de toda la cadena de suministro [1], y representan alrededor del 20% de los costos totales de esta. Dentro de las operaciones de los almacenes y CEDIS, la preparación de pedidos (picking) es la más costosa al representar 50%–70% del costo operativo total de un almacén [2]. En consecuencia, es prioritario minimizar distancias y tiempos de recorrido [3], debido a que representan más del 50% del costo del picking, y aproximadamente el 90% del tiempo total de picking [4]. Por otro lado, dentro de las configuraciones de los almacenes, la consideración de múltiples pasillos transversales permite aumentar la eficiencia de los recorridos del picking [5], disminuyendo la distancia recorrida necesaria para cambiar de un pasillo a otro.

A pesar que muchas metaheurísticas se han presentado en la literatura, la optimización por colonia de hormigas (ACO) es la metaheurística más popular para solucionar el PRP [6], y brinda mejor desempeño que otras metaheurísticas para diferentes tipo de TSPs [7]. Entre los estudios que más se destacan para solucionar el PRP a través del ACO en almacenes 2D de múltiples bloques, no se modelan las distancias entre cada par de posiciones de almacenamiento que pertenecen a un mismo bloque o a múltiples bloques, por lo cual no se garantiza que el tiempos y distancia de recorrido entre cualquier par de posiciones a visitar en un tour sea mínima. Este estudio ofrece una formulación de distancia de recorrido adaptada para configuraciones de almacenes de múltiples bloques 2D.

2 Definición del Problema

El PRP para almacenes 2D, al clasificarse como un Steiner TSP, puede formularse como un TSP clásico si se calculan previamente las distancias mínimas entre cada par de ubicaciones de almacenamiento i y j (d_{ij}), lo cual se puede lograr a través de matrices de distancia entre todas las posiciones de almacenamiento. Para esto, dadas dos posiciones de picking $i = (x_{\mathrm{i}}, y_{\mathrm{i}})$ y $j = (x_{\mathrm{j}}, y_{\mathrm{j}})$, la distancia de Manhattan d_{ij} entre *i* y *j* tal que $1 \leq i \neq j \leq L$ se calcula a través de la Ecuación (1) cuando *i* y *j* pertenecen al mismo pasillo y bloque. La Ecuación (1) igualmente se utiliza cuando *i* y *j* pertenecen a diferentes bloques, indiferente del pasillo en que se encuentren. Cuando *i* y *j* pertenecen a diferentes pasillos en el mismo bloque, la Ecuación (2) se emplea, garantizando las distancias mínimas entre *i* y *j*.

$$d_{ij} = |x_i - x_j| + |y_i - y_j| \tag{1}$$

$$d_{ij} = |x_i - x_j| + min\{|y_i - T| + |T - y_j|, |y_i - F| + |F - y_j|\} \tag{2}$$

Para formular el modelo matemático del PRP, se considera un conjunto *L* de posiciones de almacenamiento, un subconjunto *S* de posiciones de almacenamiento, d_{ij} como la distancia mínima entre dos posiciones de almacenamiento *i* y *j*. La función objetivo minimiza la distancia total recorrida, y las restricciones aseguran que cada posición de almacenamiento pueda visitarse a lo sumo una vez en cada ruta, garantizan solo un predecesor y sucesor a cada posición de almacenamiento, evitan cualquier sub-tour para que las soluciones representen un solo tour, y definen las restricciones de dominio de las variables.

3 Optimización por Colonia de Hormigas

El ACO fue diseñado para solucionar el TSP con el fin de encontrar una longitud cíclica mínima para visitar un nodo cada vez, dado un conjunto de *n* nodos, donde d_{ij} representa la distancia entre el nodo *i* y el nodo *j*, y η_{ij} representa la visibilidad del arco *ij*, que permite elegir con mayor probabilidad al arco ij que tengan mayor visibilidad. Al inicio del ACO, todos los arcos ij tienen la misma cantidad de feromona $\tau_{ij} = \tau_0$, y se lanzan

K hormigas a recorrer la red de nodos, partiendo del nodo origen (Depot). Cada hormiga busca su propio recorrido, de tal forma que cada hormiga k al estar en un nodo *i* elige pasar a otro nodo *j* según una probabilidad definida P_{kij}, que depende de la distancia d_{ij} y de la cantidad de feromona presente en el arco *ij* (τ_{ij}).

El ACO brinda memoria a cada hormiga (M_k) a través de una lista tabú que guarda los nodos que ha visitado la hormiga k y prohíbe volver a estos nodos hasta que se completa un viaje, garantizando siempre soluciones factibles. Se termina un ciclo en el algoritmo cuando todas las hormigas han realizado un recorrido completo, y luego de esto se calcula la longitud del camino más corto encontrado entre todas las hormigas. Con esta información se actualiza el valor de la feromona τ_{ij} en cada arco *ij* al reducir dichos valores a través de la evaporación de feromona, y al aumentar la cantidad de feromona de los arcos que componen la ruta más corta encontrada entre todas las hormigas. Luego de que se completa un ciclo en el que todas las hormigas han construido una ruta factible, el proceso del algoritmo se repite hasta alcanzar el máximo número de iteraciones planificadas.

4 Experimentos

Se realiza un ajuste de parámetros para garantizar un mejor desempeño para solucionar el PRP, a través de 2 x 3 x 2 x 2 = 24 escenarios que corresponden a (α,β)×ρ×*K*×iteraciones, y en cada escenario se ejecutan 10 réplicas, generando así 240 corridas experimentales. Igualmente, se evalúan diferentes valores de τ_0 para establecer la feromona inicial. Como resultado, los valores parámetros sugeridos para el ACO propuesto son α=1, β=5, ρ=0.7, *k*=20, *iter*=30, $\tau_0 = \tau_{ij}(0) = \eta_{ij}$, garantizando un mejor desempeño en distancia recorrida y menores tiempos de computación para el algoritmo. Se adicional también el operador de cataclismo se utiliza para mejorar la eficiencia del ACO y evitar óptimos locales.

Una vez establecidos los parámetros del ACO, se realizan los experimentos para establecer el desempeño del algoritmo bajo diferentes escenarios de operación, y frente a la distancia recorrida que ofrecen otros métodos de ruteo del picking que se utilizarán como *benchmarks* tales como la heurística S-shape, la heurística Aisle-by-Aisle y los algoritmos genéticos (AG), de los cuales se toman los parámetros y operadores propuestos por [8]. Los escenarios se componen por el número de posiciones de almacenamiento a visitar (10, 20, 30) que se eligen aleatoriamente en cada corrida, número de pasillos del almacén (5, 10, 20), número de posiciones de almacenamiento por lado de cada pasillo (5, 10, 20), y número de bloques del almacén (2, 3), para un total de 3 x 3 x 3 x 2 = 54 escenarios, y en cada escenario se corrieron 10 réplicas del ACO, para un total de 540 corridas experimentales. Se aclara que se crean instancias propias de experimentación, debido a que instancias conocidas como las de [9] ofrecen instancias experimentales para almacenes con dos bloques y tres pasillos transversales, pero no para almacenes de tres bloques y cuatro pasillo transversales, tal y como se requiere para este estudio.

5 Resultados

Con base en los experimentos realizados, el ACO ofrece ahorros en promedio del 7.7%, 15.1%, y 22.8% frente al AG, S-shape y Aisle-by-Aisle respectivamente. Igualmente, se identifica que el ACO ofrece ahorros de hasta el 21.0% frente al AG, ahorros de hasta el 36.1% frente a la S-shape, y ahorros de hasta el 43.6% frente al Aisle-by-Aisle. Del mismo modo, el ahorro del ACO en distancia recorrida frente al Aisle-by-Aisle y S-shape incrementa a medida en que se requiere visitar un menor porcentaje de las posiciones del almacén en un tour (posiciones a visitar / posiciones de almacenamiento). El efecto del número de bloques sobre el desempeño del ACO evidencia que a mayor número de bloques se obtiene mayores ahorros por parte del ACO frente al AG, S-shape y Aisle-by-Aisle, demostrando la eficiencia del algoritmo propuesto para almacenes multibloque. En este sentido, al pasar de 2 a 3 bloques, el ACO aumenta 2.7 veces el ahorro frente al AG, aumenta 1.9 veces frente al S-shape y 1.6 veces frente al Aisle-by-Aisle.

Para validar la significancia de los resultados obtenidos, se aplica una prueba *t* de *Student* con la cual se identifica que la media de la distancia recorrida del ACO es significativamente menor (a un nivel de confianza del 95%, valor-p < 0.05) a la media brindada por la heurística S-shape y Aisle-by-Aisle, lo cual va en línea con los mayores ahorros en distancia recorrida identificados previamente. Al comparar la media del ACO con la media del GA no se obtienen diferencias significativas a un nivel de confianza del 95%, lo cual representa que ambos métodos son eficientes para solucionar el PRP, sin embargo, se recomienda el uso del ACO al brindar frente al GA ahorros en distancia recorrida de hasta el 21%.

En cuanto al tiempo de cómputo, el ACO requiere de mayor tiempo para encontrar soluciones respecto a lo requerido por el AG. Estos valores son de esperarse, debido a que se ha probado en otros estudios que el ACO induce mayores tiempos de computación que los algoritmos genéticos [4]. Sin embargo, los tiempos de cómputo obtenidos son viables en entornos de simulación y aplicables a futuros escenarios reales, requiriendo hasta 12.9 segundos para sugerir una ruta de picking.

6 Conclusiones

Este artículo propone un ACO para minimizar la distancia recorrida en almacenes 2D multibloque, considerando una formulación de distancias mínimas entre cada par de posiciones de almacenamiento para solucionar el problema del ruteo del picking (PRP) como un Steiner TSP. A través de experimentos de simulación se ajustaron los parámetros más relevantes del ACO, y se demostró que el ACO presenta mejor desempeño respecto al AG, S-shape, y Aisle-by-Aisle, por lo cual, el algoritmo propuesto puede mejorar el desempeño de las operaciones de picking en almacenes y centros de distribución, brindando soluciones satisfactorias para la distancia recorrida en tiempo de cómputo viables para entornos operativos.

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A decision support tool for the location routing problem during the COVID-19 outbreak in Colombia

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Abstract. During the outbreak of coronavirus disease 2019 (COVID-19) in Bogotá, Colombia, some strategies for dealing with the increasing number of infected people and the level of occupation of intensive care units include the use of Personal Protective Equipment (PPE). PPE is a crucial component for patient care and a priority for protecting health-care workers. For attending this necessity, the location of distribution centers within the city and the corresponding routes to supply the intensive care units (ICU) with PPE have an important role. Formally, this problem is defined as the Location Routing Problem (LRP). The LRP is an NP-Hard problem that combines the Facility Location Problem (FLP) and the Vehicle Routing Problem with Multiple Depots (MD-VRP). This work presents a decision support tool based on a simheuristic method that hybridize an Iterated Local Search (ILS) algorithm with Monte Carlo simulation to deal with the LRP with uncertain demands. Realistic data from Bogotá (Colombia) was retrieved using Google Maps to characterize the geographical distribution of both potential facilities and ICUs, while demands were generated using the uniform probability distribution. Our preliminary results suggest the competitiveness of the algorithm in both the deterministic and the stochastic versions of the LRP.

Keywords: COVID-19, Healthcare Logistics, Location-Routing, Decision support tool, ILS, Monte Carlo simulation.

1 INTRODUCTION

In December 2019, a new coronavirus disease emerged characterized as a viral infection with a high level of transmission in Wuhan, China. Coronavirus 19 (COVID-19) is caused by the virus known as Severe Acute Respiratory Syndrome coronavirus 2 (SARS- CoV-2) established by the Coronaviridae Study Group of the International Committee on Taxonomy of Viruses (ICTV) [1]. As the cumulative numbers of confirmed cases have considerably increased worldwide, academics and practitioner are mainly concerned about modeling and prediction of COVID-19 ([2], [3]).

In Colombia, according to the report of August 4th, 2020, 33.9% of the cases are located in Bogotá D.C. (capital city) with 113,548 confirmed cases, and the 89.2% of the total intensive care units are occupied [4]. As COVID-19 is predominantly caused by contact or droplet transmission attributed to relatively large respiratory particles which are subject to gravitational forces and travel only approximately one meter from the patient [5], personal protective equipment (PPE) has become crucial for protecting healthcare workers and alleviating the burden in the hospitals and controlling the epidemic [6].

Considering the city needs and that most of the studies about COVID-19 deal with prediction models and do not integrate their results to support decision making, e.g., estimating cities' implications, supplies and demand of material resources; in this paper, we study the location of distribution centers within the city and the corresponding routes to supply PPE to the Intensive Care Units (ICU) and, therefore, support decision making. The problem is formally defined as the Location Routing Problem (LRP). The LRP involves all decision levels in supply chain management and logistics, i.e., strategic, tactical and operational. From an operations research perspective, it can be seen as the combination of two well-known NP-Hard problems such as the Facility Location Problem and the Vehicle Routing Problem with Multiple Depots. Thus, the LRP is also NP-Hard.

From a practical point of view, there is a recent trend to create both easy-to-implement and powerful algorithms when solving complex problems. Accordingly, in this work, we propose a simheuristic method based on an ILS algorithm in which initial solutions are created using a random choice of depots combined with a biased randomized version of the nearest neighbor heuristic. Readers are referred to [7] as a key literature review of simheuristics for dealing with stochastic combinatorial optimization problems. Moreover, with the aim of providing an easy-to-use tool, we have implemented our algorithm as an Excel Macro, considering its advantages in data manipulation, consolidation and analysis. Our preliminary results have been compared to the ones obtained by GAMS/Cplex for the deterministic LRP, showing promising results. Besides, we have carried out a set of experiments for the LRP with Stochastic Demands by combining our Iterated Local Search (ILS) algorithm with Monte Carlo simulation (MCS). The results on the stochastic version demonstrate that using safety stocks as protective policies against uncertainty could improve not only expected costs but also the reliability of the obtained solutions.

The remainder of this paper is organized as follows: section 2 presents the literature review; section 3 introduces the description of the problem; section 4 outlines the proposed approach; in section 5 we analyze the obtained results; finally, section 6 presents some conclusions and further research perspectives.

2 LITERATURE REVIEW

This section presents a brief literature review focusing on location routing problems and also on logistics applications for pandemics such as the current one generated by Covid-19.

2.1 Location Routing Problems

The LRP was initially proposed by [8]. Due to its complexity, the first studies on the LRP proposed to tackle it by separating the two related subproblems, i.e., the facility location problem and the vehicle routing problem. However, it has been demonstrated that such approach leads to sub-optimal solutions [9]. This complex problem can be used to support decision-making processes in different fields of application such as city logistics, humanitarian logistics, horizontal cooperation, among others ([10], [10], [11]).

Considering its NP-Hard nature, heuristics and metaheuristics yield better results than classical optimization approaches, specially for large sized instances [12]. We refer to [13] for an overview on LRP problems. The deterministic version of the LRP has been widely studied while its stochastic counterpart has been scarcely analyzed. In the stochastic demands version, the main assumption is that demands are not known in advance, i.e., the real value of demands is revealed once the vehicle arrives at the customer. Thus, routes failures will occurs whenever the aggregated demand in a route exceeds the vehicle capacity [14].

Among recent works on the LRP with stochastic demands (LRPSD), Quintero et al. [14] proposed a simheuristic algorithm to deal with the LRPSD. The authors proposed three simulation processes to deal with: (i) the estimation of the right safety stock policy to protect against uncertainty, (ii) estimate stochastic costs and reliabilities of the proposed solution, (iii) refinement of the estimation of both stochastic costs and reliabilities. However, their work was tested using benchmark instances adapted from literature, while in this work we use realistic data from Bogotá, Colombia related to the current pandemic.

2.2 Logistic approaches for dealing with COVID-19

Mainly, most of the literature on COVID-19 is focused on prediction models (e.g., [2], [3], [15]). Torrealba-Rodriguez et al. [2] studied the prediction of cases of COVID-19 infection in Mexico. Shen [15] considered the logistic growth modelling of COVID-19 proliferation in China and its international implications. Wang et al. [3] predicted the global trend and the specific trends of Brazil, Russia, India, Peru and Indonesia.

However, just few works integrate the results of the prediction models to support decision making. For example, Loske [16] analyzed the impact of COVID-19 on transport volume in German food retail logistics, as well as its resulting implications. The author proposed a regression analysis to validate the interdependencies of COVID-19 and transport logistics in retail logistics, and considered the reallocation of health care capacity, repurposing of hospitals, and close collaboration between the government and the health care committee. Zhang et al. [17] deal with the scheduling of vehicles to transport infected people to isolated medical areas and solved it using a metaheuristic approach. Yu et al. [18] propose the design of a multi-objective reverse logistic network in epidemic outbreaks. More specifically, this work aims to determine the location of temporary facilities

and transportation of the increased medical waste generated by a pandemic. Kaplan [19] combines predictive and prescriptive models for Covid related decision making such as crowd-size restrictions, hospital surge planning, timing decisions (when to stop and possibly restart university activities), and scenario analyses to assess the impacts of alternative interventions, among other problems.

To the best of our knowledge there are no published works on the location of depots and the consequent routing of PPEs (maks, gloves and disposable suits) for caregivers (physicians, nurses, therapyst, etc) located all long the city. Thus, the importance and novelty of this work.

3 PROBLEM DESCRIPTION

Due to the COVID-19 pandemic and its associated effects, many governments have adopted lock-down mechanisms as a strategy to diminish the speed of contagion and have more prepared health systems, especially by having a higher number of available ICUs. Particularly, in Bogotá - Colombia, lock-down started in March 2020 but currently, we are facing a high number of new cases and deaths every day. Besides, the occupancy of ICUs is becoming critical with a 90% value. Thus, logistic approaches are a must to optimize the response of the system to the current pandemic.

In particular, we aim to analyze the efficient delivery of PPE (composed by masks, gloves, and disposable suits) required by medical teams (physicians, nurses, and therapists) to take care of COVID-19 patients. In this work, we propose to study the location of distribution centers within the city and the corresponding routes to supply the different ICUs that are habilitated to receive COVID-19 patients in Bogotá. This situation could be represented by the Location Routing Problem with Stochastic Demands (LRPSD) due to the nature of the field of application.

The LRP considered in this work is adapted from [20]. As stated by [21], the LRP belongs to the class of NP-hard problems, which means that it is not possible to find optimal solutions for large-sized instances in reasonable computing times. The LRP is defined in a directed graph $G = (V, A, C)$. V is a set of nodes comprising a subset I of m possible depot locations and a subset $J = V \backslash I$ of n customers. The cost of any arc $a = (i, j)$ in the arc set A is given by C_a. A capacity W_i and an opening cost O_i are associated with each depot site $i \in I$. Each customer $j \in J$ has a demand d_j. A set K of identical vehicles of capacity Q is available. When used, each vehicle incurs a fixed cost F and performs one single route. The following constraints must be taken into account:

- Each demand d_j must be served by one single vehicle.
- All nodes are allocated to an open depot.
- The number of depots within the set must guarantee that total demand can be serviced.
- Each route must begin and end at the same depot and its total load must not exceed vehicle capacity.

– The total load of the routes assigned to a depot must respect the capacity of the selected depot.

The goal of our problem is to determine the subset of distribution centers (DCs) to open, allocate ICUs to DCs, and planning the routes from DCs to serve ICUs, in order to minimize the total expected costs. The total expected costs of a solution include the fixed cost of opening facilities F, the costs of traversed arcs, the fixed cost of using vehicles and the cost of recursive actions (in case of route failures due to the stochastic demands). The mathematical model of the stochastic version can be found in [14].

Figure 1 depicts a complete solution for our LRP. Potential distribution centers locations are represented by squares while ICUs are represented by circles. This figure illustrates how, from an initial problem setting (top-left), a complete solution could be obtained by *(i)* selecting the distribution centers to be opened (top-right), *(ii)* assigning ICUs to open DCs (bottom-left) and, *(iii)* creating routes from each DC to its allocated ICUs (bottom-right), while satisfying all constraints.

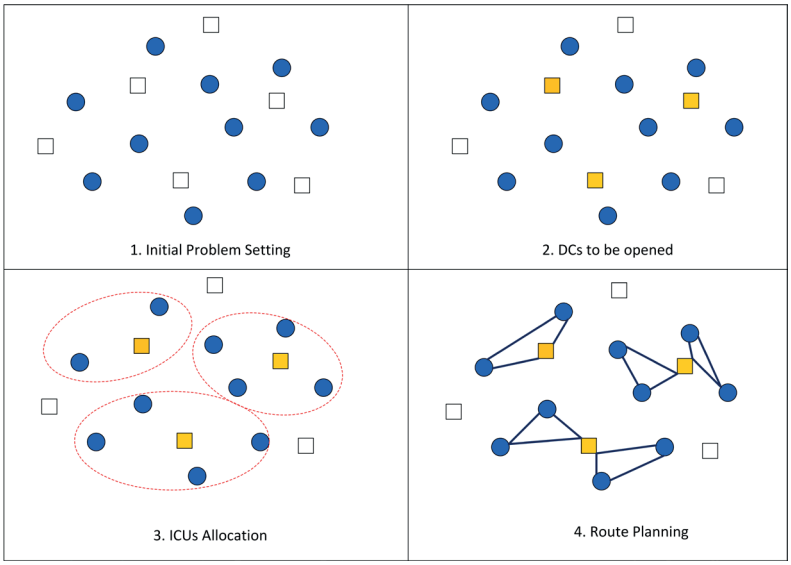

Fig. 1. A Complete Solution for our LRP

4 SOLVING APPROACH

To deal with the LRPSD, we have developed a simheuristic algorithm hybridizing an Iterated Local Search (ILS) algorithm [22] with Monte Carlo simulation. The

procedure is driven by the ILS while the simulation is used to test the quality of the solution in the stochastic setting of the problem. Considering that ILS is a powerful local search-based metaheuristic to deal with deterministic problems, we need to use a kind of protection policy (safety stocks) to face uncertainty and get better results in the stochastic setting of the problem.

Safety stock is used when planing routes to reduce the possibility of not serving some ICUs, when executing the planned routes, due to demand uncertainty. However, after a certain value (too conservative) of safety stock, expected costs tend to increase due to excessive deterministic costs. The idea, then, is to find the most convenient safety stock policy providing the best trade-off among costs and reliability.

Our proposed method is composed of three main phases: *(i)* location phase, *(ii)* customer allocation and, *(iii)* vehicle routing. To deal with the location decisions, we randomly open depots until the total available capacity is enough to serve total demands. Then, in the allocation phase, ICUs are randomly selected and assigned to the nearest open depot with the available capacity to serve it. Besides, the available capacity of the corresponding depot is updated and the ICU is marked as assigned. This process is repeated until all nodes have been allocated to an open depot. In case that a given ICU can not be assigned to any open depot due to capacity constraints, a new depot is opened and the customer is allocated to it. Here, solution failure due to depot capacity it is not considered. In the routing phase, the starting node for each route is randomly selected. Next, a modified version of the nearest neighbor heuristic is applied. A route finishes when the next customer to be added to the route can not be served due to vehicle capacity constraints, so the vehicle is sent back to the depot.

This three-phase process is executed during a given number of iterations and we keep the best solution found among them. The aforementioned solution is sent to a short simulation process to estimate stochastic costs and reliabilities. Stochastic costs are generated when a planned route can not serve a certain ICU and, as a consequence, a corrective round-trip from such ICU to the depot is executed to re-load the vehicle and resume the planned route. After the short simulation, the ILS framework is executed. To do so, we propose as a perturbation operator the interchange of an open depot with a closed depot, i.e., a previously open depot is closed and a previously closed depot is opened. The ICU is assigned to the closing depot are allocated to the opening one. A graphical representation of this operator can be seen in Figure 2. Moreover, two local search operators have been designed. The first one is the exchange of two customers among different routes from the same depot [23](see Figure 3 top) while the second one is the exchange of two customers from routes belonging to different depots (see Figure 3 bottom).

Promising solutions obtained by the ILS framework are passed through the short simulation process. Next they are stored in a pool of solutions which is sorted by increasing costs. Finally, the top-10 solutions stored within the pool are passed through a more intensive simulation process to refine both stochastic costs and reliabilities. The process is depicted in Figure 4.

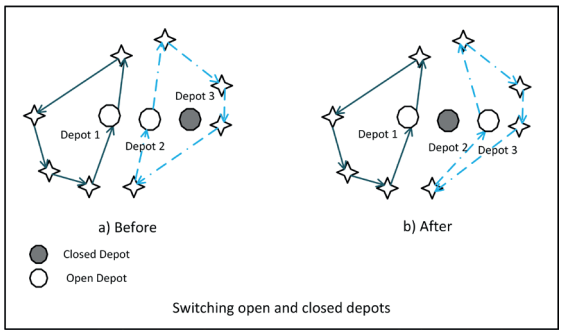

Fig. 2. Diversification Operator

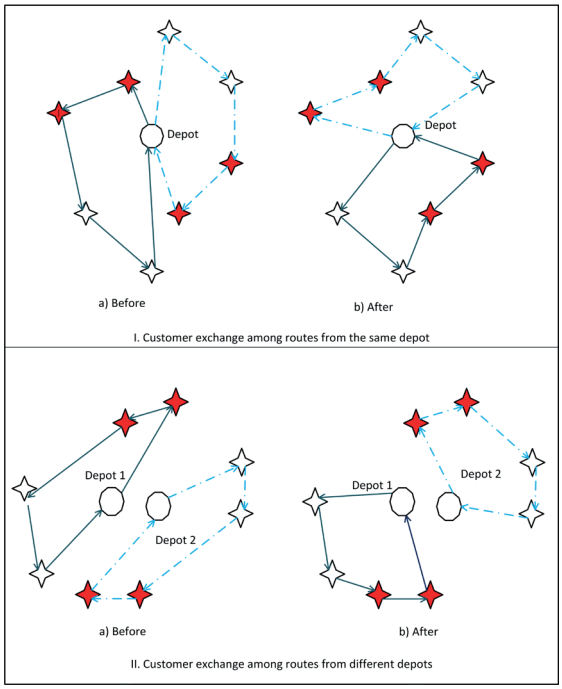

Fig. 3. Local-Search Operators

The reliability $reliab_r$ for each route r in solution S is computed as follows:

$$reliab_r = (1 - \frac{\sum_{n=0}^{TotalSimulationRuns} RouteFailures}{TotalSimulationRuns}) * 100\% \quad (1)$$

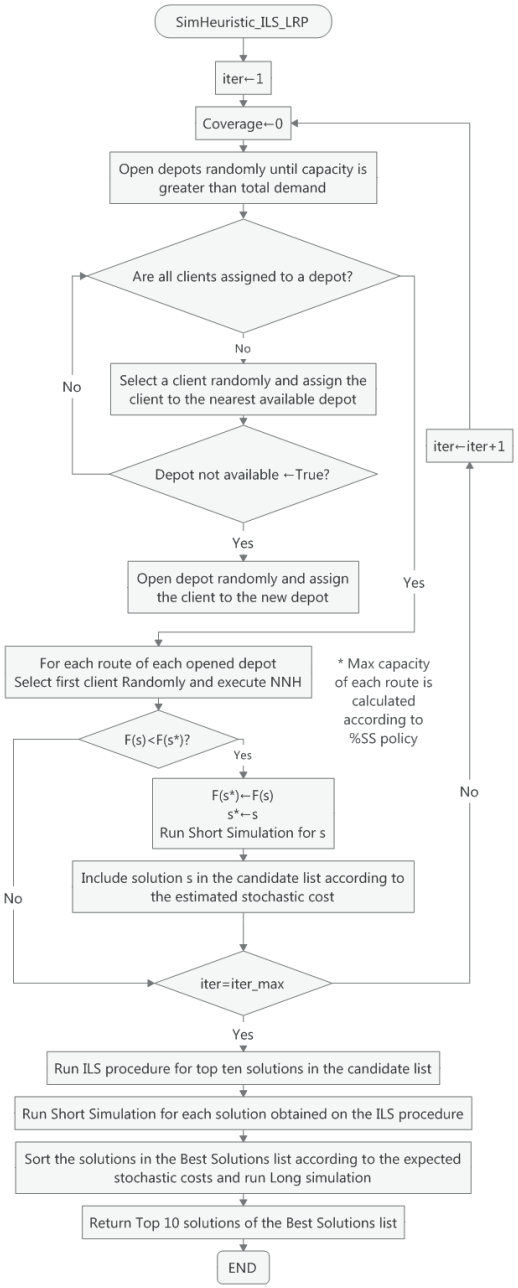

Fig. 4. Flowchart of the proposed method for the LRPSD

It is important to note that each route within a solution could be seen as an independent component of a series system, i.e., the proposed solution will fail if, and only if, a failure occurs in any of its routes ($RouteFailures$). Therefore, the reliability index of a solution S with R routes can be calculated as $\prod_{r=1}^{R} reliab_R$.

5 RESULTS AND ANALYSIS

The proposed algorithm was coded as an Excel macro using the Visual Basic for Applications (VBA) language. The version used for the spreadsheet was MS Excel 2013. As stated by [24], using spreadsheet-based solutions have several advantages such as interface familiarity, ease of use, flexibility, and accessibility. Moreover, since MS Excel is largely known around the world, using it as the engine for the spreadsheet provides additional benefits, such as integration with software packages that offer built-in functionalities to obtain/send data from/to MS Excel, and the possibility of customizing code in Visual Basic for Applications ([24]). It is also important to mention that using spreadsheet-based solutions may result in low-cost solutions that may yield significant savings for enterprises, especially in non-developed countries.

We have tested our proposed method using different instances with real locations in Colombia. Instances were generated by retrieving -from Google Maps- latitude and longitude coordinates belonging to retailing and warehousing points located in Bogotá (Colombia's main city and its capital). The expected value for demands corresponds to the PPE required for each ICU assuming that each patient is served by a team consisting of one physician, one nurse, and one therapist. The team visits each patient once per hour, so 24 visits are required during a complete day. The capacity of DCs was generated to guarantee the satisfaction of total demands. Opening costs, in US Dollars, for each facility corresponds to real construction costs of warehouses in Bogotá. The vehicle capacity corresponds to the real-load capacity of the Renault Kangoo, which is a vehicle broadly used in Colombia to execute urban distribution tasks. Instances considers 53 ICUs, 10 distribution centers, the distance matrix and variations on demands. The instances are named MQS-BOG#, where # identifies the number of the instance. All instances are available in https://cutt.ly/SpreadsheetSimheuristicILS.

All deterministic instances were modeled using the GAMS modeling language. However, due to the complexity of the problem, the Cplex solver was unable to find a solution after eight hours of execution time. Thus, we generate a set of reduced instances to have a fair comparison between the exact method and our proposed algorithm. To generate the reduced instances, we run our heuristic method and we get two open depots and their allocated customers from our best reported solution. Additional depots were randomly selected while ensuring the capacity to serve all ICU demand. All reduced instances are available in https://cutt.ly/ReducedInstances. The experiments were carried out using a standard windows PC with Intel® Core™ i7 – 6th generation and 8Gb RAM. Each instance was solved using five different random seeds. The obtained re-

sults are summarized in Table 1. GAMS/Cplex column shows the best solution reported by this software for each instance after 27,000 secs of computational time. It is worth mentioning that none of the solutions was proven as optimal. OBDS is the best deterministic solution reported by our algorithm among all executions, while OADS is the average value of the obtained solutions. Besides, GAP shows the percentual gap of OADS concerning GAMS/Cplex. We can see that, on average, our algorithm has an average gap of 1.64% compared to the results provided by GAMS/Cplex.

Table 1. Results - Deterministic Case

INSTANCES	SUB-PROBLEM	GAMS/cplex(1)	OBDS(2)	GAP% (2)-(1)
MQS-BOG1	1	2,558,514.72	2,558,516.65	0.00008%
MQS-BOG1	2	2,389,528.66	2,389,529.89	0.00005%
MQS-BOG1	3	2,401,725.86	2,401,728.02	0.00009%
MQS-BOG1	4	2,806,031.04	2,806,034.95	0.00014%
MQS-BOG1	5	2,818,227.57	2,818,233.07	0.00020%
MQS-BOG1	6	2,649,244.88	2,649,246.32	0.00005%
MQS-BOG2	1	1,972,433.46	2,231,267.37	13.12257%
MQS-BOG2	2	2,558,516.41	2,558,519.50	0.00012%
AVERAGE				1.64041%

As this work concerns the stochastic version of the LRP, we have transformed the deterministic instances by assuming their demands as the expected value (EV) of the stochastic case. Besides, stochastic demands are revealed once the vehicle arrives at the UCIs by using the uniform probability distribution $\sim U[EV - 10\%, EV + 10\%]$. It is worth to mention that any other probability distribution according to the real demand's behavior could be used.

Our proposed method was tested using five different random seeds and different safety stock policies as a security buffer to handle demand uncertainty i.e., 0%, 1%, 3%, 5% and 7%. The results are presented in Table 2. The setup time for the simheuristic was 7 minutes without including the simulation time. For each safety stock policy, the best stochastic solution (OBSS), the average of our top 10 stochastic solutions (OASS-10), the expected reliability of the OBSS (Reliab.), and the Gap among OBSS and OASS-10 are reported. It is worth to mention that the top 10 solutions for each of the instances tested with each safety stock policy show the same location decisions, clients allocation are similar and the major differences among them are due to the configuration of each route. Furthermore, Figure 5 shows the behavior of expected stochastic costs and reliabilities for a given instance when using different safety stock policies. As expected, when no protection is considered there are many route failures due to demand uncertainty. Therefore, we can see higher costs and lower reliability. On the other hand, when the value of safety stock policy increases, costs tend to decrease while reliability increases; however, when the safety stock is greater than 5%, costs start to increase again. Similar situation occurs for the different instances, i.e., costs start to decrease when the percentage of safety stock is increased and, at a certain point (ideal safety stock policy), the costs

reach its minimum value. After that value, costs become higher. This situation occurs when decision-makers for protecting against uncertainty, tend to greatly increase the % of safety stock for augmenting reliability and, therefore, costs are increased due to a higher number of planned routes.

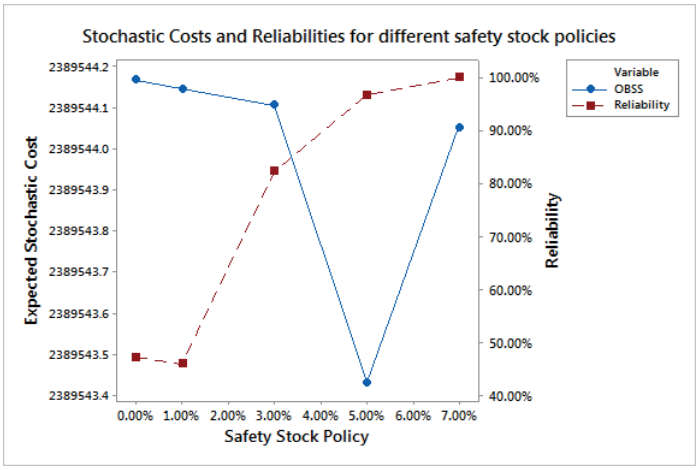

Fig. 5. Average Values of Expected Costs and Reliabilities of Our Best Stochastic Solutions for Different Safety Stock Policies

Moreover, in Figure 6 we present the Best Deterministic Solution (OBDS) for a given instance against the two best performing stochastic solutions with a safety stock policy of 5%. Besides generating lower expected stochastic costs, the stochastic solutions, even if they are not the optimal ones, show less variability than the deterministic one in the stochastic case.

6 CONCLUSIONS

This article has presented a decision support tool based in a hybrid method consisting of an Iterated Local Search algorithm combined with Monte Carlo simulation to deal with the Location Routing Problem with stochastic demands. This version finds applications in humanitarian logistics and last-mile deliveries problems. Our proposed method was tested using five different instances generated with Google Maps to characterise the geographical distribution of customers. Besides, different safety stock policies are tested.

Results show the behavior of the expected stochastic costs and reliabilities when using different safety stock policies per each tested scenario. Furthermore, results also show that this version of the LRP is a hard problem and its complexity increases according to the level of uncertainty. As expected, when no

Table 2. Results - Stochastic Case

Safety Stock Policy	0%				1%				3%			
Instance Name	OBSS	OASS-10	Reliab.	Gap	OBSS	OASS-10	Reliab.	Gap	OBSS	OASS-10	Reliab.	Gap
MQS-BOG1	8,602,359,004.19	8,602,362,316.87	33%	0.000039%	8,602,358,922.17	8,602,360,060.80	52%	0.000013%	8,602,358,781.84	8,602,360,594.29	75%	0.000021%
MQS-BOG2	11,888,198,383.13	11,888,200,758.20	17%	0.000020%	11,888,199,113.51	11,888,200,274.41	49%	0.000010%	11,888,197,027.05	11,888,201,121.57	75%	0.000034%
MQS-BOG3	18,747,950,727.91	18,747,951,361.18	47%	0.000003%	18,747,943,157.57	18,747,946,203.56	46%	0.000016%	18,747,947,581.35	18,747,948,413.29	82%	0.000004%

Safety Stock Policy	5%				7%			
Instance Name	OBSS	OASS-10	Reliab.	Gap	OBSS	OASS-10	Reliab.	Gap
MQS-BOG1	8,602,356,349.06	8,602,359,573.59	94%	0.000037%	8,602,358,584.88	8,602,360,081.83	100%	0.000017 %
MQS-BOG2	11,888,197,767.40	11,888,200,352.42	97%	0.000022%	11,888,195,544.36	11,888,198,946.79	100%	0.000029%
MQS-BOG3	18,747,943,818.55	18,747,946,987.14	97%	0.000017%	18,747,950,202.88	18,747,952,654.84	100%	0.000013%

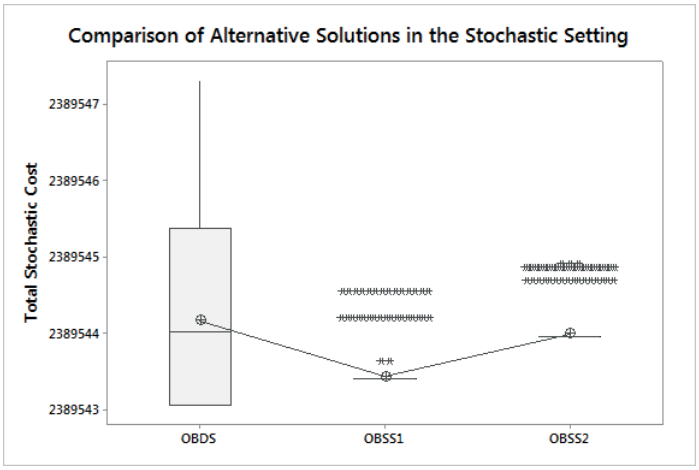

Fig. 6. Example of Behavior of Alternative Solutions in the Stochastic Setting

protection is considered there are many route failures due to demand uncertainty and higher costs and lower reliability are obtained. On the other hand, when the value of safety stock policy reach the ideal value, costs tend to decrease while reliability increases.

Regarding future research, there is a room for including other representations for uncertainties and to design other approaches for handling them. Moreover, adaptation for large scale problems will be also considered.

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Simulated Annealing metaheuristic approach for generating alternative corridor locations

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Abstract. This article presents a metaheuristic approach applying simulated annealing for the problem of planning corridors for oil pipelines facilities. The corridor location problem requires finding an optimal or a set of sub-optimal alternative routes between two locations, accounting for cost optimization and topographical constraints. The proposed simulated annealing applies a path-based search for exploring the space of possible routes. The experimental evaluation solves realistic problem instances considering real information of Veracruz, Mexico. The proposed approach is able to compute a set of near-optimal alternative routes that improve up to 34.1% of the terrain impact cost over a greedy pathfinding reference method, such as the ones included in traditional geographical information systems.

Keywords: Corridor location, simulated annealing, path analysis, shortest path optimization

1 Introduction

The right-of-way (ROW) or *corridor* is a crucial requirement for the construction of linear installations such as pipelines, electric transmission lines, roads, among others [19]. The planning process of real corridors must consider legal, social, political, environmental, engineering, and economic factors, which make the design process complex [17]. Proper planning of ROW explores different paths based on design specifications, environmental laws, and good practices to determine the best option, which is the goal of the corridor location planning [4].

The corridor location problem (CLP) can be modeled as an optimization problem, subject to topographic constraints such as distance, obstacles, environmental impact, and safety [19]. Locating a corridor is analogous to identifying the shortest or least-cost path for the facility to be designed on a landscape [26]. Traditional approaches to solve the corridor location problem are based on generating a set of alternate routes through enumerative methods [24], using penalty techniques [14], or by specifying one or multiple intermediate points where the route must pass [22] depending on the size of the area across the landscape where the corridor could pass [8]. The problem of generating alternate routes has led

researchers to develop solution methods that use different types of representation of the domain, through graphs; they use deterministic shortest path methods, such as Dijkstra and its variants to get only one path at a time (optimal route). However, the Dijkstra algorithm and its variants are costly, since the computing time to find the shortest path using exact methods increase based on the network size. For this reason, additional mechanisms generating more than one route at a time are useful contribution in this area.

Geographical Information Systems (GIS) facilitate the management of geographic information using raster (2D grid of measurable numerical characteristics of the projected area) and vector (representation of the projected area through points, lines, and polygons) data models. The efficient handling of the data models affects map analysis speed. Distance measurement permits identifying the optimal path by an accumulated surface cost raster layer (ASC) performed on spatial analysis [7],[2]. ASC raster layer represents a weighted graph associating a value (weight) on every edge on an appropriate scale that corresponds to the goals and objectives for every raster cell involved in the corridor design. Generally, GIS tools use the Dijkstra algorithm and its variants for the spatial analysis, without considering the generation of alternate routes [10]. Unlike exact techniques, metaheuristics cannot guarantee to obtain the optimal solution to a problem. However, metaheuristic techniques are more efficient than exact techniques in solving complex optimization problems [20]. Simulated Annealing (SA) is a metaheuristic method that finds reasonable solutions for combinatorial problems over large solution spaces [12]. SA implements a local search guided through a stochastic process with a given probability. The quality solution can be improved using a neighborhood search in the SA algorithm. The neighborhood structure allows searching for approximate solutions, adjusted to the complexity and nature of the problem [6].

In this line of work, this article presents a SA metaheuristic approach for the CLP. The space exploration allows computing different alternatives routes between origin and destination points, generating competitive and spatially different routes alignments. Realistic problem instances are solved in the experimental evaluation, using real information of the Veracruz state, a well-know oil production area in Mexico. Accurate results are reported: the proposed SA allows computing a spatially diverse set of near-optimal alternatives that improves up to 31.4% the results of traditional methods included in GIS software.

The rest of the article is structured as follows. Section 2 describes the corridor location problem and the optimization model of the shortest route. Section 3 describes the proposed SA metaheuristic approach, including the method for generating the initial solution. Section 4 provides details of the experimental evaluation of the proposed approach, including the description of the real scenarios and the discussion of the results. Additionally, the corridor paths obtained by the proposed SA are displayed on GIS software. Finally, Section 5 presents the conclusions and formulate the main lines for future work.

2 The corridor location problem

This section describes the corridor location problem, presents its mathematical formulation, and reviews related works about traditional approaches to solve the problem based on enumerative methods, penalty techniques, and by specifying intermediate points where the path must pass.

2.1 Problem description

In the construction of linear facilities such as pipelines, communication networks, transmission lines, etc., it is essential to permit access to public land that will house the facilities. Therefore, one of the factors to consider is the use of existing or new ROWs [19],[15]. Specific laws demand considering alternative routes in a ROW project to determine the optimal route for the corridor across public and private terrains. In the context of line-based facilities, two important concepts are distinguished, depending on the location perspective: in a path, the facility is placed on an existing network composed of street/road segments and intersections; instead, a corridor is open in terms of being a route that lies anywhere on the landscape [5]. The linear facility design process is split into two stages. In the first stage, the best compromise route is determined, based on the objectives of the interested parties. In the second stage, the engineering and construction design and the facility accessories must be included in the design process [17]

This work focuses on the first stage of the facility design process. The goal is to generate alternative routes, to be analyzed in a posterior decision-making process to determine a proper route for corridor location. Relevant attributes are considered for route generation, including a cost function that considers topographical information and the height of the candidate locations for the route.

2.2 Mathematical Formulation

The CLP is formulated as the problem of finding the shortest path between source and destination in an undirected weighted graph $G = (N, A, h, c)$ [26].

The graph G represents a Cartesian grid used to discretize the area where the corridor is to be built. $N = \{u_1, u_2, ..., u_n\}$ is the set of graph nodes. Each node represents the center of a cell in the rectangular grid specified by a point (x, y, z), where z is a non-negative integer value based on the digital elevation model (DEM), and x, y are in terms of latitude and longitude coordinates from the Universal Transversal Mercator (UTM) reference system. Each grid cell is linked to its eight neighboring cells. $A = \{(u_{i1}, u_{j1}), (u_{i2}, u_{j2}), ..., (u_{im}, u_{jm}\}, u_{ik}, u_{jk} \in N$ is the set of edges; $n = |N|$ and $m = |A|$. An edge $(u_i, u_j) \in A$ connects nodes u_i, and u_j. Function $h : N \to \mathbb{Z}^+$ assigns a non-negative height (the *elevation*) to each node. In turn, function $c : A \to \mathbb{R}^+$ defined by Eq. 1, assigns a non-negative cost to each edge $(u_i, u_j) \in A$.

$$c(u_i, u_j) = \frac{\sum_{k}^{|L|} L^k(i, j)}{|L|} \tag{1}$$

In Eq. 1, $L^k : \{1, ..., n\} \times \{1, ..., n\} \rightarrow \mathbb{R}$ is the k-th *topographic layer* considered for the area where the corridor is to be built. Each topographic layer represents specific information about roads, buildings, land use, and other relevant features about the terrain, and values for each cell (i, j) are classified on a zero to ten scale, according to a passing penalty between node u_i and node u_j. Higher passing penalty are associated to higher costs.

The problem proposes finding the minimum-cost path from a given source node s to a destination node t. The objective function to minimize (Eq. 2a) represents the total viability cost of edges chosen for the path. In the proposed formulation, each edge (u_i, u_j) has associated a binary decision variable x_{ij} that is equal to 1 if the edge is included in the optimal shortest path and 0 otherwise.

$$\min f(x) \quad = \sum_{(u_i,u_j)\in A} c(u_i, u_j) \cdot x_{ij} \tag{2a}$$

subject to

$$\sum_{(u_i,u_j)\in A} x_{ij} - \sum_{(u_j,u_i)\in A} x_{vu} = \begin{cases} 1 \text{ if } u_i = s \\ -1 \text{ if } u_i = t, \\ 0 \text{ if } u_i \neq s, t. \end{cases} \tag{2b}$$

$$x_{ij} \in \{0, 1\} \quad \forall (u_i, u_j) \in A \tag{2c}$$

$$h(u_i) \leq DEM_{max} \tag{2d}$$

Eq. 2b express the flow conservation constraint, ensuring that the computed path starts on the origin node $s \in N$ and ends on the destination node $t \in N$. Eq. 2c is the integrity constraint for the binary decision variable x_{ij}. Finally, Eq. 2d is the elevation penalty constraint, which states that node u_i avoid steep slopes in the path through an established maximum height (DEM_{max}) for the corridor route location.

2.3 Related work

The iterative penalty method assigns penalty parameters to the edges of the graph once one of them has been selected to be part of a solution. The efficiency of the algorithm depends on the penalty strategy implemented. Regardless of the penalty strategy, many alternatives generated are parallel lines to each other. The method was initially proposed for road design [24] and used for routing hazardous materials delivery [11], among other applications. Lombard and Church [14] introduced the Gateway Shortest Path method (GPS), based on a shorter route problem with restrictions. It generates a short route called "Gateway Shortest Path" between a source and a destination, restricted to pass through a specific node (the *gateway*). The method allows identifying different acceptable alternate routes, with less computational effort than the iterative penalty method.

A different approach for generating alternate routes is the kth-shorter routes (KSR) method [25], which generates a classified list of the k lowest cost routes. After generating the first route, KSR excludes one edge from the network included in the solution; the network is modified iteratively to generate different alternatives. A similar method is Near-Shortest Path (NSP) [3], which generates k routes within a specific costs range, without classifying them.

Other proposed methods for generating alternate routes for corridors are Minimax [13] and p-dispersion [1]. The Minimax method is a greedy approach that begins by generating the shortest k routes between an origin and a destination, to build a subset of different routes. The p-dispersion method generates a broad set of candidate routes and selects a subset of p routes using a dispersion model that maximizes the minimum difference between any pair of selected routes. In contrast, Scaparra and Church [22] extended the GPS method by considering multiple gateway points to generate more complex paths, but with a higher computational cost.

Other approaches make use of parallel computing to run parallel methods such as KSR and NSP [16]. Exact algorithms guarantee to find the optimal global solution; however, in the worst case, the computation times can be exponential depending on the size of the problem [9]. The computation time and effort scale to the extent that solving the problem is intractable for realistic problem instances [8]. An alternative solution to deal with this type of problem is through non-deterministic heuristics, capable of generating optimal solutions in reasonable computation time. Zhang and Armstrong [26] proposed Multi-Objective Genetic Algorithm for the Corridor Selection Problem (MOGADOR), which generates a wide set of Pareto optimal and near-optimal solutions. The objective functions that it minimizes calculate the suitability of the accumulated corridor aligned to engineering costs, environmental cost, and socioeconomic cost. Experimental results showed that MOGADOR, through the designed and implementation of specific genetic operators for corridor alternatives outperforms conventional approaches based on shortest path algorithms, both in terms of computational complexity and the quality of generated route alternatives, contributing to GIScience-based spatial analysis.

3 The proposed SA for the CLP

This section describes the proposed SA metaheuristic approach to solve the CLP.

3.1 Simulated Annealing method

Simulated annealing is a stochastic search algorithm based on a heat treatment process by altering the structure of a solid in order to change its properties [12]. The annealing process requires heating and then slowly cooling the solid to obtain a robust structure [23]. In the annealing process, the free energy of the solid minimized; that is, the atoms of the solid moves freely (i.e., randomly) on high temperatures, and then the atoms are rearranged themselves through lower

temperatures, producing a minimum energy state of the system. The cooling schedule permits gradually to decrease the temperature until it reached an equilibrium state. However, if the solid is cooled too quickly or the initial temperature of the annealing is too low, a higher energy state would reach arriving into an amorphous state. An analogy is formulated between the annealing of solids and an optimization problem to solve. The system state corresponds to a solution of the optimization problem; the free energy of the system is analogous to the objective function cost of the problem to be optimized; the slight system state change (perturb the system state) is analogous to a local search of solutions into a solution neighborhood (correspond to the mutation operator used on Evolutionary Algorithms); the cooling schedule corresponds to the control mechanism of the parameters (initial temperature, equilibrium state, cooling function, stopping criteria or final temperature) in SA algorithm; the final system state (frozen state) corresponds to the final solution by the SA algorithm (global optimum).

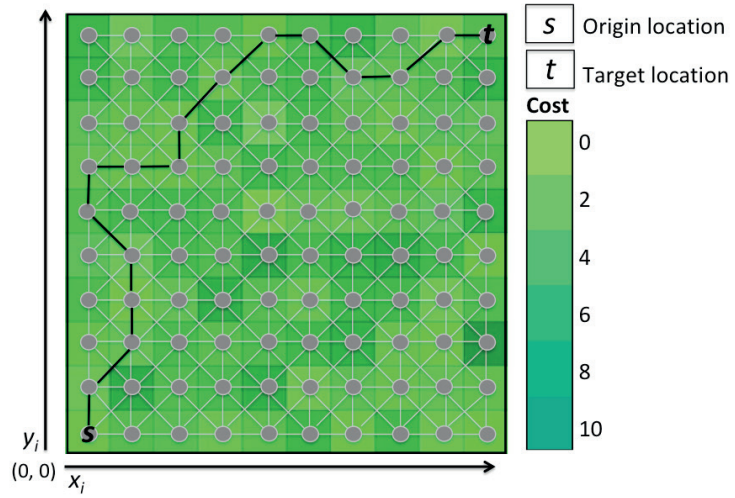
SA consists of empowering an iterated local search method through a procedure that allows accepting lower quality solutions than the current solution to escape from local optimum. In this way, SA explores and exploits the search space to find better solutions [20]. The SA process begins with high temperatures where random changes are accepted, altering the initial state continuously, with a slight decrease in temperature. In this way, the number of accepted changes decreases until none change is accepted. Finally, the process converges and stops with a profoundly modified initial state. SA is an iterative local search guided through a stochastic process, where a j state is accepted with a determined probability given by $\Pi(\Delta E, T) = exp^{-\Delta E/kT}$, where k is the Boltzmann constant. The Metropolis algorithm [18] simulates the change of energy in the cooling process of a physical system. SA works over a representation of candidate solutions, defined according to the specific features of the problem to solve.

The iterative method requires an initial solution, which is generated by applying a random initialization procedure or using a heuristic method incorporating knowledge of the problem. The exploration is performed changing the system state (candidate solution), which corresponds to generate local movements in the neighborhood of the current state. This state change is applied in order to increase diversity in the search. Once the state is slightly perturbed, if the energy change produced by the perturbation is negative, the new system state is accepted; otherwise, if it is positive, it is probabilistically accepted according to the Boltzmann distribution function. The starting temperature must be balanced between high and low values to conduct the local search in enough time to allow movements in the neighborhood. The initial temperature decreases gradually (cooling), if the decrease in temperature is slowly, better solutions obtained but with more significant computation time. The equilibrium state at each temperature must permit to apply sufficient movements proportional to the neighborhood size. Finally, the stopping criterion is related to the final temperature parameter, which is regularly a low value, near to zero.

3.2 SA for the CLP

The main features of the proposed SA algorithm for the CLP are described next.

Solution representation. A two-dimensional representation is used to encode candidate solutions for the CLP in the proposed SA. Two vectors of integer numbers ($\vec{x}$ and $\vec{y}$) are used to encode a path $p = \{u_0, u_1, \cdots, u_k\}$ between a source node s and a destination node t ($u_0 = s$, $u_k = t$). Value (x_i, y_i) in the representation correspond to the indexes of the i-th node in the path, in the Cartesian grid used to discretize the area where the corridor is to be built. Fig. 1 presents a sample representation for a CLP solution from origin $s = (0, 0)$ to destination $t = (9, 9)$ on a 10×10 grid discretizing a given terrain.



Y	0	1	2	3	4	5	6	6	6	7	8	9	8	8	9	9
X	0	0	1	1	1	0	0	1	2	2	3	5	6	7	8	9

Fig. 1: Sample representation for a CLP solution from origin $s = (0, 0)$ to destination $t = (9, 9)$ on a 10×10 terrain

Objective function. The proposed SA for CLP minimizes the cost function defined in the mathematical formulation (Eq. 2a).

Initial solution. The initial solution of SA for CLP is generated using an uninformed search, according to the pseudocode presented in Algorithm 1. Starting from the origin node, the neighboring node with the lower cost is selected in each iteration step, applying the Queen's movement (orthogonal plus diagonal), a standard method to reduce infeasible solutions in continuous terrain and increase cell connectivity that allows improving the accurate distance measurement by up to 30% over other movements [26].

Algorithm 1: Uninformed search for SA for CLP initialization

Data: $G(N, A, h, c)$, source node $s \in N$, target node $t \in N$
Result: Vector path $p = \{u_0, u_1, \cdots, u_k\}$

```
Create a queue q = ∅                                   ▷ queue of nodes
Create a vector p = ∅                                  ▷ path to return
q.push(s)
p.push(s)
Label s as visited
while ! q.empty() do
    u_i = q.pop()
    if u_i == t then
        return vector p                          ▷ destination node reached
    else
        for each adjacent node u_j of u_i
        if !visited(u_j) then
            Label u_j as visited
            q.push(u_j)
            p.push(u_j)                              ▷ include node in path
        end
    end
end
```

Algorithm 1 uses a queue structure q to store nodes of the graph. The process starts from the origin node s. This node is enqueued into q. Then, the process explores the adjacent neighbor node u_i before moving to the next level neighbors. If u_i is the destination t, the process finishes and returns vector p; otherwise, the procedure selects an adjacent node u_j of u_i and evaluates if has not been visited; in this case it is selected, marked as visited, queued into q and into the path vector p. Subsequently, u_j becomes the current node and the process of selecting its adjacent nodes is repeated until finding the destination node t.

Exploration. The exploration operator randomly selects two points of the current solution and explores alternate routes through prohibited and guided movements. Both random points must be different from the origin and destination, and different from each other. The random points are labeled as new starting point s_{new} (the nearest point to the origin s) and new destination point t_{new}. A pseudo-random path is created between s_{new} and t_{new}. Two criteria are considered to avoid infeasible solutions: if there is any common point between the current solution and the pseudo-random path, the solutions are merged in that point to create a new solution; otherwise, an A^* pathfinding algorithm is used to merge both paths and create a new feasible solution.

Annealing schedule. A geometric update scheme is applied for the temperature, i.e., $T^{k+1} = \alpha T^k$. The value of α is set by empirical analysis (see section 4).

Stopping criterion. A fixed effort stopping criterion is applied: SA-CLP stops when the temperature reaches a fixed minimum value (determined empirically).

Algorithm 2 presents a pseudocode of the proposed SA for the CLP. The main difference with a canonical SA method is the information stored during the search. SA is a memoryless search algorithm; i.e., it only use information from the last step of the search to compute a new solution. However, the CLP requires a set of efficient and spatially different route alternatives. Thus, up to n_S local optima solutions are stored in a vector P during the local search process.

Algorithm 2: Proposed SA for the CLP

```
k = 0
initialize(s_k)                                   ▷ generate initial solution
T_k = T_max                                       ▷ initialize temperature
P(n_S) ← ∅                                        ▷ initialize the vector of solutions
while T_k < T_f do
    i = 0                                         ▷ Markov chain iterator
    while i < maxL do
        s^{k+1} = perturbation(s^k)               ▷ exploration
        if f(s^{k+1}) < f(s^k) then
            s^k ← s^{k+1}                         ▷ acceptance criterion
        else
            Δf = f(s^{k+1}) − f(s^k)
            Π(Δf) = exp^{−(Δf/T_0)}
            β = random(0,1)
            if β ≤ Π(Δf) then
                s^k ← s^{k+1}                     ▷ accept sub-optimal solution
            end
        end
    end
    insert(P, s^k)                                ▷ store in solutions vector
    T_k ← αT_k                                    ▷ temperature decay
    i ← i + 1
end
return s^k
```

SA starts from the initial solution s^0 and proceeds to search for feasible solutions through an iterative local search in the neighborhood of size $N(s)$. At each iteration, a perturbed neighbor s^{k+1} is generated. Feasible perturbed solutions that improve the cost function (Eq. 2a) are always accepted. Perturbed solutions that do not improve cost are accepted according to a probability that depends on the current temperature T_k, and the Boltzmann probability function $\Pi(\Delta f)$). A maximum number of iterations (maxL) are performed to analyze different perturbed solutions in a Markovian search with the same value of the temperature parameter. The value of maxLenght is set by empirical analysis, accounting for the computational cost and the number of improved solutions in the Markovian search. The SA algorithm stops when the temperature reaches the final value T_f determined by empirical analysis (see section 4).

This way, the proposed metaheuristic approach determines the optimal route between two points across a geographic terrain for the CLP. Likewise, space exploration allows generating different alternatives routes between origin and destination points for competitive and spatially different route alignments in the corridor location. The next section analyzes the experimental results of the proposed approach.

4 Experimental results and discussion

This section describes the experimental evaluation of the proposed SA for the CLP. Details about the platform used for development and execution are presented. Likewise, the studied scenario and problem instances are described. Experimental results of the parameter calibration are reported. Finally, results for the addressed real-world problem instances are reported and discussed.

4.1 Development and execution platform

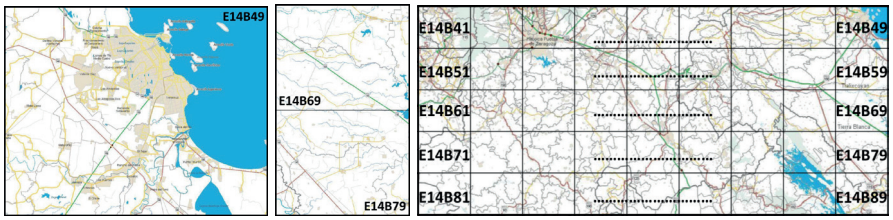
The proposed SA method was developed in C++11 and evaluated on a Quadcore Xeon E5430(2.66GHz), 8GB RAM, from National Supercomputing Center (Cluster-UY), Uruguay [21]. QGIS 3 was used for data visualization.

4.2 Studied area and problem instances

The studied area is located in Veracruz State, on the Gulf of México. Veracruz State has a territorial surface of 71 699 km^2. The Veracruz Basin is an essential depot of gas and petroleum with an area of 34 824 km^2, containing a potential number of oil extraction wells that distribute to other regions of Mexico.

Four problem instances were built using GIS data models of the studied area. Tested instances include remarkable spatial objects considered in a real-world pipeline facility construction. The assigned penalty impact cost to the spatial objects are: industrial facilities, airports, port lighthouse, runway aviation and bridges (10), electric substations, railways, port facilities, sports facilities and communication lines(9), water channel, water bodies, water ponds (human consumption), aqueducts, sand mining zones, cemeteries, urban areas and buildings (8), watershed, communication facilities (7), highways and rural locations (6), streets, racetracks, flood zones, rural paths and oil ducts/pipelines (5), green areas (not protected areas), sandy soils and growing areas (0). The DEM data model used has a raster BIL format, and each spatial object has a vector shapefile format. The UTM coordinates information of the spatial objects was converted from BIL raster to ASCII-TXT format using QGIS3, and from shapefile format to ASCII-TXT format using OGR/GDAL and Phyton 3. The methodology to build each problem instance considers creating an ASC raster through weighting the penalty impact costs of the spatial objects used from each topographic chart, using Eq. 1.

Problem instances #0 and #1 include the municipality of Veracruz (topographic chart E14B49); problem instance #2 includes the municipalities of Naranjos (E14B69) and Tierra Blanca (E14B79); and problem instance #3 includes part of the territories of Morelos, Puebla, and Veracruz states (E14B41-49, E14B51-59, E14B61-69, E14B71-79, and E14B81-89). Fig. 2 shows the topographic charts of the tested problem instances at map scale 1:50,000.



(a) #0 and #1 (b) #2 (c) #3

Fig. 2: Problem instances in the studied area, at map scale 1:50,000

4.3 Parameters configuration

The SA parameters must be adjusted to determine the configuration that allows computing the best results. Parameters tuning is made by an empirical sensitivity analysis performed over problem instance #0. The studied parameters and candidate values included: $T_0 \in \{2.0, 1.3, 0.9, 0.3, 0.1\}$, $T_f \in \{10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$, $\alpha \in \{0.99, 0.98, 0.97, 0.96, 0.95\}$ and maxL $\in \{100, 50, 20, 10, 5\}$. Due to the stochastic quality of the simulated annealing, statistical analysis was applied to select the best configuration. 30 independent executions of SA were performed. Then, the Shapiro-Wilk test was applied to check normality. Results discarded the normality hypothesis with p-value $< 10^{-2}$. Thus, the Kruskal-Wallis (KW) non-parametric test was applied to analyze the differences between the results distributions. Table 1 reports the comparative analysis for each parameter value studied. The parameter values that allowed computing the best results on the tested instance (marked in bold in Table 1), with statistical significance according to the KW test were $T_0 = 2.0$ (KW p-value 0.017), $\alpha = 0.98$ (KW p-value 0.006), maxL $= 50$ (KW p-value 0.0016), and $T_f = 10^{-6}$ (KW p-value $> 10^{-2}$). Figure 3 graphically shows the behavior of the studied cooling schedule parameters values for the parameter setting instance.

4.4 Experimental results

A greedy strategy was implemented as a baseline for evaluating the results of the proposed SA-CLP. The greedy algorithm iteratively builds solutions taking local optimal decisions at each step (i.e., the adjacent node with the lowest cost is selected to be included in the path). When no feasible node is available to be selected, the method returns and chooses the second-best adjacent node. The procedure is repeated until reaching the destination node.

Table 1: Results of the sensitivity analysis of SA-CLP parameters

T_0	$f(s^k)$ worst	$f(s^k)$ best	$f(s^k)$ median	α	$f(s^k)$ worst	$f(s^k)$ best	$f(s^k)$ median
2.0	3024.40	2049.51	**2096.15**	0.99	2915.40	2046.41	2127.45
1.3	2915.40	2046.41	2127.45	0.98	2856.50	2046.40	**2073.05**
0.9	2566.40	2047.51	2133.80	0.97	3356.40	2057.30	2138.91
0.3	3215.30	2047.81	2120.95	0.96	2829.00	2046.01	2117.05
0.1	2306.90	2106.00	2211.35	0.95	2269.10	2080.30	2161.75
maxL	$f(s^k)$ worst	$f(s^k)$ best	$f(s^k)$ median	T_f	$f(s^k)$ worst	$f(s^k)$ best	$f(s^k)$ median
100	3630.70	2054.21	2112.06	10^{-2}	3636.70	2048.80	2136.45
50	2543.20	2047.41	**2099.15**	10^{-3}	3195.50	2047.61	2128.40
20	2916.10	2047.81	2118.15	10^{-4}	2916.10	2047.81	2118.15
10	2688.10	2083.71	2132.55	10^{-5}	2745.00	2061.51	2156.80
5	2306.90	2106.00	2211.35	10^{-6}	2853.60	2051.40	**2108.95**

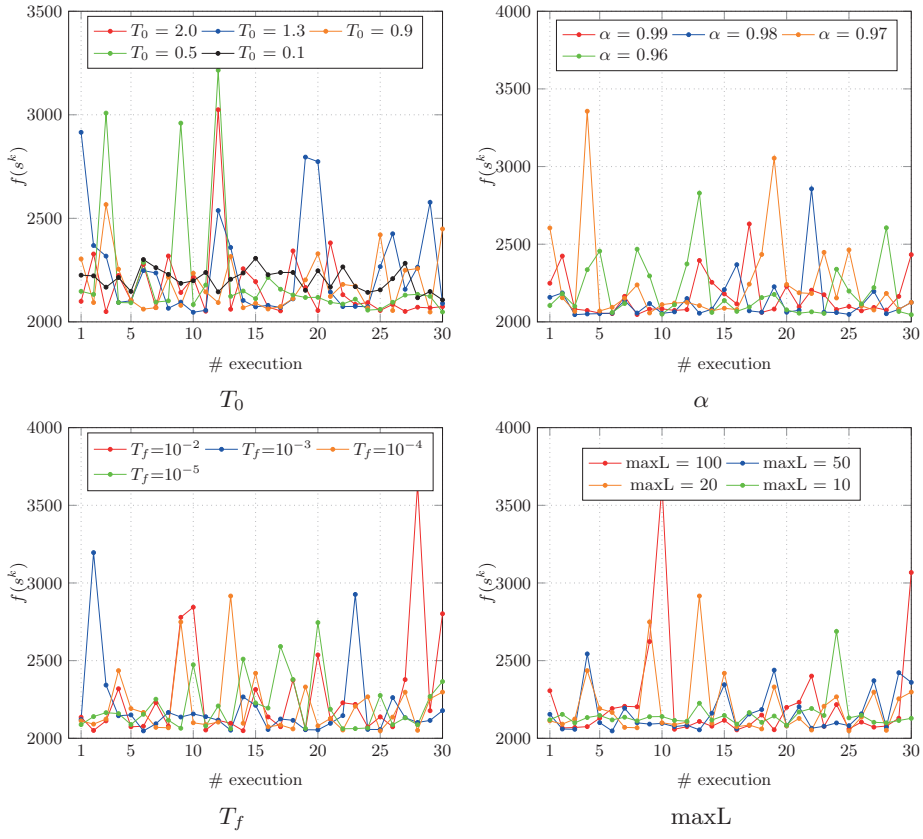


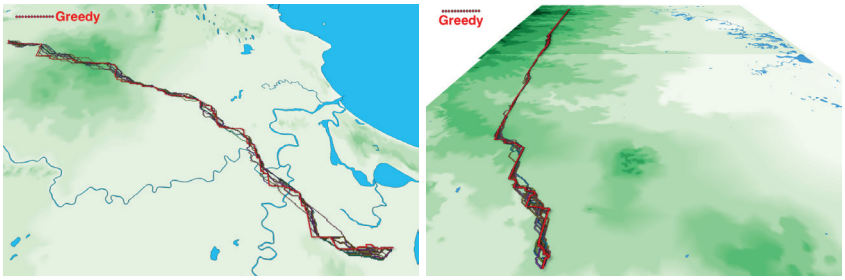
Fig. 3: Sample results of the sensitivity analysis for problem instance #0

Table 2 reports the median of the best objective function values ($\overline{f(SA)}$) computed by the SA-CLP and the comparison with the reference algorithm ($f(greedy)$). The relative improvement on objective function values (Δ_f) over the reference algorithm are also reported.

Table 2: Cost solutions for the studied problem instances

instance	size	origin, destination	$f(greedy)$	$f(SA)$	$\overline{f(SA)}$	Δ_f
#0	586×732	(44,365) (512,50)	3202.2	**2048.6**	2109.2	34.1%
#1	586×732	(292,551) (537,8)	2413.6	**1835.0**	2010.2	16.7%
#2	585×1467	(24,264) (113,1071)	9350.7	**7785.2**	8267.1	11.5%
#3	5341×6727	(221,47) (2525,6073)	63622.4	**55164.9**	57340.7	9.8%

Results in Table 2 indicate that the proposed SA-CLP is able to improve significantly over the greedy algorithm, regarding the cost function values. Considering the baseline results computed by the greedy algorithm, improvements of up to 34.1% were obtained in problem instance #0. Also, the solutions computed by the SA-CLP were between 9% and 16% better than the greedy algorithm in problem instances #1, #2, and #3. SA-CLP computed significantly competitive and slightly spatially different routes alignments on every problem instance. The SA-CLP execution with the parameter values reported in subsection 4.3 allows computing 492 different alternative routes between origin and destination points for the problem instances #0 and #1. For problem instances #2 and #3, SA-CLP computed 452 routes alignments each one. The competitive and spatially different route alignments for corridor location are displayed using a GIS tool. Figure 4 shows two samples of alternative routes for the corridor location in problem instances #1 and #2.



(a) Problem instance #1 (b) Problem instance #2

Fig. 4: Alternative routes for corridor location

5 Conclusions and future work

This article presented a metaheuristic approach to solve the CLP, a relevant problem related to the construction of linear facilities such as pipelines, electric transmission lines, and roads. A SA metaheuristic was applied to generate different and competitive alternative routes between origin and destination points.

The proposed exploration pattern applies an uninformed search for initialization and a specific exploration operator that modifies randomly selected subsegments of the current solution. Alternate routes are explored through prohibited and guided movements, and the A* pathfinding algorithm is applied for merging. Furthermore, the standard memoryless search pattern in SA is extended to store a vector of local optima solutions to be considered as alternative routes.

The experimental evaluation focused on four realistic problem instances defined over real information of the Veracruz state, a well-know oil production area on the Gulf of Mexico. Parameters configuration was performed via a sensitivity analysis that studied four relevant SA parameters: initial and final temperature, the decay factor of the annealing schedule and the length of the Markov chain used for exploration. Statistical analysis were applied to study the results distribution by checking normality and determining the significance of the median values for each parameter configuration. Using the best configuration from the previous analysis, the proposed SA allowed computing a spatially diverse set of near-optimal alternative routes that improves up to 34.1% the results of a greedy algorithm, such as the ones included in traditional GIS software.

The main lines for future work are related to extend and improve the neighborhood search to address the reduction of improvements over the traditional greedy approach when solving large problem instances, e.g., by applying hybrid approaches combining exact and metaheuristic methods. The experimental evaluation of the proposed approach should also be extended to consider a larger number of synthetic and real scenarios. Multiobjective versions of the problem and multiobjective metaheuristics should be studied to compute and analyze distance and penalty impact cost simultaneously.

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Algoritmo evolutivo híbrido basado en la división del espacio de los objetivos para el problema de la mochila bi-objetivo

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Resumen Este trabajo presenta un Multi-objective Evolutionary Algorithm (MOEA) el cual divide el espacio de los objetivos (OSD), en varias regiones utilizando la solución Nadir calculada ésta en cada generación del algoritmo. Para la clasificación de las soluciones de las distintas regiones en frentes no-dominados, se utilizan diferentes estrategias de optimización de las funciones objetivo. La idea es intensificar la diversidad del frente aproximado de soluciones no-dominadas alcanzado. El algoritmo propuesto (NSGA-II/OSD) se implementa sobre el algoritmo NSGA-II y se ensaya sobre el Problema de la Mochila Bi-objetivo (0-1 MOKP). Con baja dimensionalidad (2-3 objetivos), este problema es de difícil resolución para un MOEA dado el elevado número de soluciones superpuestas que se generan durante su evolución. El método propuesto ofrece muy buen desempeño cuando es comparado con los algoritmos NSGA-II y MOEA/D muy reconocidos ambos en la literatura especializada.

Palabras clave: Algoritmos evolutivos multi-objetivos , Optimización, Bi-objectivo Problema de la Mochila

1 Introducción

Un problema de optimización multiobjetivo (POM) es aquel que corresponde a una cierta realidad industrial, económica o de otra índole y sobre el que un decisor desea optimizar varios objetivos usualmente en conflicto entre sí. Cuando se resuelve un POM de complejidad difícil, métodos metaheurísticos son muy apropiados. Estos métodos no grantizan obtener el frente exacto de soluciones no-dominadas, pero sí un conjunto aproximado.

La segunda generación de algoritmos evolutivos multiobjetvo (MOEAs), ha demostrado obtener excelentes resultados resolviendo POM [1]. De naturaleza estocástica, los MOEAs están basados en el concepto de población de soluciones lo que les proporciona gran destreza para encontrar múltiples soluciones no-dominadas en espacios de soluciones de diversa naturaleza. NSGA-II [2] y MOEA/D [3] son entre otros [4], [5], [6], [7], dos MOEAs muy reconocidos en la comunidad científica multiobjetivo. El primero, utiliza una clasificación de rangos por dominancia como mecanismo de convergencia, mientras que crowding-distance es el mecanismo usado para diversificar las soluciones. El segundo, funciona descomponiendo el POM en un número de subproblemas escalares o mono-objetivos que son resueltos todos a la misma vez mediante la evolución de una población de soluciones. Algunos trabajos recientes describen dificultades en cuanto a la especificación del punto de referencia en MOEA/D [4], [8], [9],[10]. Trabajos con MOEAs que incluyan un sub-división del espacio de los objetivos como la propuesta en este trabajo son muy escasos, sólo hemos encontrado [11], [12].

El problema de la mochila multiobjetivo en variables binarias (0-1 MOKP) es un problema combinatorio bien conocido y ampliamente manejado en la comunidad multi-objetivo. Un considerable número de métodos exactos y metaheurísticos, ver por ejemplo [3], [13], [14], intentan resolver este problema. En [15], se señala el elevado número de soluciones superpuestas (overlapping solutions) cuando los MOEAs se aplican a problemas combinatorios con muchas variables de decisión y baja dimensionalidad. La aparición de soluciones superpuestas cuando el Problema de la Mochila 0-1 (2-3 objetivos) se resuelve con un MOEA, tiene un significativo impacto negativo sobre la diversidad del frente aproximado final de soluciones no-dominadas alcanzado [15].

Se propone en este trabajo un híbrido de NSGA-II, el cual divide el espacio de los objetivos (OSD) en varias regiones utilizando la solución Nadir la cual es calculada en cada generación del algoritmo. Las distintas subdivisiones utilizan diferentes estrategias de optimización de las funciones objetivo. La idea que subyace es intensificar la diversidad de soluciones del frente óptimo aproximado de Pareto (POF) alcanzado, permitiendo que en cada generación del algoritmo, soluciones dominadas por los extremos del POF alcanzado puedan entrar en la población N no-dominada.

El resto del trabajo se organiza de la siguiente manera. En la sección 2 se presentan algunos conceptos básicos para entender mejor este trabajo. En la sección 3 se describe el método propuesto. Los resultados experimentales se detallan en la sección 4. Por último, en la sección 5 se presentan las conclusiones.

2 Conceptos básicos

En términos de minimización, un POM puede ser definido de la siguiente forma:

$$\begin{array}{ll} Min. & F(x) = f_1(x), f_2(x), ..., f_n(x) \\ s.a. & \\ & g_k(x) \leq 0 \qquad k \in (1, 2, ..., p) \\ & h_l(x) = 0 \qquad l \in (1, 2, ..., q) \end{array} \tag{1}$$

donde $F(x)$ es el vector de objetivos a minimizar y $n \geq 2$ el número de objetivos. Las ecuaciones $g_k(x) \leq 0$ y $h_l(x) = 0$ representan respectivamente p restricciones de desigualdad y q restricciones de igualdad. Los valores de x que satisfacen el conjunto de las $(p + q)$ restricciones, definen el espacio realizable S. El vector $x = (x_1, x_2, ..., x_m) \in S$ es un vector solución de m variables de decisión.

El conjunto de las imágenes de cada solución realizable en el espacio de la decisión, conforma el conjunto de soluciones realizables en el espacio de los objetivos $Z = f(S)$ definido como $Z = \{z_1 = f_1(x), ..., z_n = f_n(x), \ \forall x \in S\}$ y donde $z = (z_1, ..., z_n) \in R^n$ representa una solución realizable en el espacio de los objetivos.

Una solución $z^t = (z_1^t, z_2^t, ..., z_n^t) \in Z$ domina una solución $z^u = (z_1^u, z_2^u, ..., z_n^u) \in Z$ y se le conoce como Pareto-óptima si se verifican las siguientes condiciones:

1. $z_j^t \leq z_j^u \qquad \forall j \in (1, 2, ..., n)$
2. $\exists j \in (1, 2, ..., n) \ \ tal \ \ que \ \ z_j^t < z_j^u$

Al conjunto de soluciones Pareto-óptimas en el espacio de soluciones se le llama conjunto óptimo de Pareto y a su imagen en el espacio de objetivos frente óptimo de Pareto.

La solución Ideal z^I de un POM es un vector solución $z^I = (z_1^I, z_2^I, ..., z_k^I)$, construido con los mejores valores función objetivo de todas las soluciones del espacio de los objetivos (Fig. 1). Esta solución es en general inalcanzable.

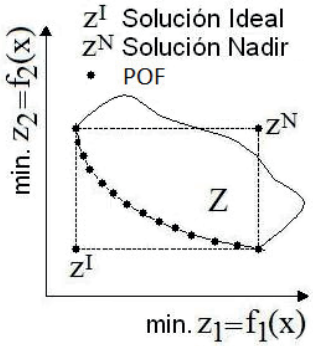

Fig. 1. Soluciones Ideal, Nadir y frente óptimo aproximado de Pareto (POF).

La solución Nadir z^N de un POM es un vector solución $z^N = (z_1^N, z_2^N, ..., z_k^N)$, construido con los peores valores función objetivo de todas las soluciones del frente de Pareto (Fig. 1). Esta solución puede ser alcanzable o inalcanzable.

2.1 MOEA/D con especificación de Zhang del punto de referencia

Básicamente, MOEA/D trabaja descomponiendo un POM en un número finito de sub-problemas escalares y resolviéndolos simultáneamente mediante la evolución de una población de soluciones. Algunos enfoques para convertir un POM en un sub-problema escalar se pueden consultar en [3]. El enfoque de Tchebycheff se expresa como sigue:

$$\begin{aligned} Min.\ \ & g^{te}(x|\lambda, z^*) = \max_{1\leq i\leq n} \{\lambda_i f_i(x) - z_i^*\} \\ s.a.\ \ & x \in X \end{aligned} \tag{2}$$

donde $z^* = (z_1^*, ..., z_n^*)$ es el punto de referencia (PR) especificado en este trabajo de la siguiente forma:

$$z_i^* = \alpha * max\{f_i(x)|x \in X\}\ para\ cada\ i = 1, ..., n \tag{3}$$

y donde $\alpha \geq 1$.

2.2 MOEA/D con especificación de Ishibuchi del punto de referencia

Ishibuchi et al. proponen en [8] usar en (2) la siguiente especificación para el PR:

$$z^R = z_i^* - \alpha_t(z_i^{max} - z_i^*) \tag{4}$$

donde $z_i^* = (z_1^*, ..., z_n^*)$ corresponde al mínimo valor en la función objetivo i, $z_i^{max} = (z_1^{max}, ..., z_n^{max})$ corresponde al máximo valor de la función objetivo i en la generación en curso y α_t es un parámetro que decrece en cada generación del algoritmo. De (4) es obvio que cuando $\alpha_t = 0$ los valores z^R y z^* tienen los mismos valores.

Para hacer que el valor z^R se aproxime gradualmente al valor del punto de referencia z^* durante la ejecución del algoritmo, el valor α_t es modificado en cada generación según:

$$\alpha_t = \alpha\ (t_{max} - t)/(t_{max} - 1) \tag{5}$$

donde α es un valor inicial de α_t, t_{max} es el número máximo de generaciones del algoritmo y t es la generación actual. Nótese que el valor final de α_t en la última generación es cero, i.e., z^R tiende a z^* durante la ejecución del algoritmo.

3 Método propuesto

El algoritmo propuesto en este trabajo consiste en una versión modificada de NSGA-II, en los siguientes términos:

1. En cada generación t del algoritmo: una población $R_t = P_t + Q_t$ es construida con P_t la población de padres de tamaño N y Q_t la población de hijos (tamaño N) generados de las operaciones de cruzamiento y mutación a partir de la población N construida en la generación $t-1$.
2. A partir de la población R_t la solución Nadir es identificada mediante algún método.
3. En base a la solución Nadir el espacio de los objetivos se divide en tres regiones independientes R_1, R_2 y R_3 tal como se indica en la Fig. 2.
4. Las soluciones de cada región R_1, R_2 y R_3 son clasificadas (complejidad computacional O(n2N)) en diferentes frentes no-dominados (F_1, F_2,...,F_n). Para la clasificación de las soluciones, se usan diferentes criterios de optimización de las funciones objetivo f_1 y f_2.
   (a) Región R_1: Las dos funciones objetivo f_1 y f_2 son siempre maximizadas.
   (b) Región R_2: La función f_1 es siempre maximizada. La función f_2 es maximizada si se cumple la condición $t \geq nt$, en caso contrario f_2 es minimizada. El valor t es la generación actual y nt un parámetro (número de generaciones que se maximiza o minimiza la función objetivo) que se define como:

$$nt = \alpha \; t_{max} \quad 0 \leq \alpha \leq 1 \tag{6}$$

   (c) Región R_3: La función f_2 es siempre maximizada. La función f_1 es maximizada si se cumple la condición $t \geq nt$, en caso contrario f_1 es minimizada.

   Finalizado el paso 4, toda la población R_t queda clasificada en frentes de no-dominación (F_1, F_2,...,F_n).
5. Para completar la población P_{t+1} hasta alcanzar un tamaño N, como en NSGA-II, las soluciones con menor rango primero, y mayor crowding-distance segundo, son escogidas.

4 Experimentos y comparaciones

4.1 Problema de la Mochila Multiobjetivo MOKP/0-1

El problema de la mochila multiobjetivo en variables binarias (MOKP/0-1) consiste en una serie de objetos o ítems con un peso, un beneficio asociado a cada uno de ellos y un límite de capacidad para cada mochila. Así, la tarea radica en encontrar el subconjunto de objetos que maximicen los beneficios totales de cada mochila y que puedan ser colocados en dichas mochilas sin exceder sus límites de capacidad. El problema es de complejidad NP-difícil y puede ser usado para modelar cualquier aplicación real que se ajuste al modelo descrito en (7).

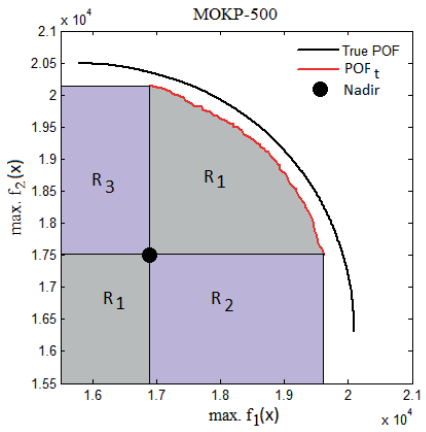

Fig. 2. División propuesta del espacio de los objetivos en base a la solución Nadir.

El MOKP/0-1 puede ser definido formalmente como sigue:

$$\begin{cases} max. \quad f_i(x) = \sum_{j=1}^{m} b_{ij} x_j \quad i = 1, ..., n \\ s.a. \qquad \sum_{j=1}^{m} w_{ij} x_j \leq c_i \qquad x_j \epsilon \{0, 1\} \end{cases} \tag{7}$$

donde: m=número de objetos, x_j=variable de decisión, n=número de sacos, b_{ij}=beneficio objeto j según saco i, w_{ij}=peso objeto j según saco i y c_i = capacidad saco i.

4.2 Configuración de parámetros y métricas

En este trabajo, las implementaciones de NSGA-II y MOEA/D se han realizado según [2] y [3]. Ambos algoritmos son aplicados sobre el 500-MOKP/0-1 con dos objetivos, los datos del problema y frente óptimo pueden descargarse de: https://sop.tik.ee.ethz.ch/download/supplementary/testProblemSuite/testProblemSuite/.

En todos los experimentos se utilizó codificación binaria, cruce uniforme de probabilidad 0.8 y probabilidad de mutación (bit a bit) de 1/500. Un número de 400000 evaluaciones de la función objetivo se usó como condición de parada. Tres tamaños de la población N=50, N=100 y N=200 soluciones fueron utilizadas en los tres algoritmos NSGA-II/OSD, NSGA-II y MOEA/D. Los valores examinados para el parámetro α definido en (6) de balance convergencia/diversidad de NSGA-II/OSD fueron α= 0.0, 0.1, 0.2, 0.3 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 y 1.0. Con MOEA/D, los valores ensayados de α en el cálculo del punto de referencia z^* según la especificación de Zhang definida en (3) fueron α= 1.0, 1.05, 1.1, 1.15, 1.2, 1.25, 1.3; en la versión de Ishibuchi para el cálculo del punto de referencia

z^R definido en (4) y (5), los valores se fijaron en α= 0.0, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0 y 10.0.

Para la comparación de los resultados obtenidos por los algoritmos, se emplearon la S-metric o hipervolumen H (punto de referencia usado el 0,0) sugerida en [16] y visualizaciones de los frentes de soluciones de Pareto alcanzados de valor H más próximo al valor medio final calculado en 30 ejecuciones independientes.

4.3 NSGA-II/OSD análisis previo: efectos de variar el parámetro α

En esta subsección se analizan las influencias en la convergencia y diversidad del frente de soluciones alcanzado, cuando se varía el parámetro α en la ecuación (6) en el algoritmo propuesto NSGA-II/OSD. En la Fig. 3 (izquierda), se muestran los valores del hipervolumen medio al modificar los valores del parámetro α. Se puede observar que los mejores valores de H se obtienen para valores intermedios del parámetro α así, el mejor valor del hipervolumen se alcanza cuando α=0.5. Para mejor interpretar estos resultados, la Fig. 3 (derecha) muestra los efectos sobre la distribución de soluciones del aproximado POF obtenido cuando N=200. Se observa que los frentes aproximados de Pareto de menor diversidad (mayor convergencia) y mayor diversidad (menor convergencia) se obtienen cuando α=0.0 y α=1.0 respectivamente; de otra parte, el mejor balance convergencia-diversidad se logra para un valor de α=0.5.

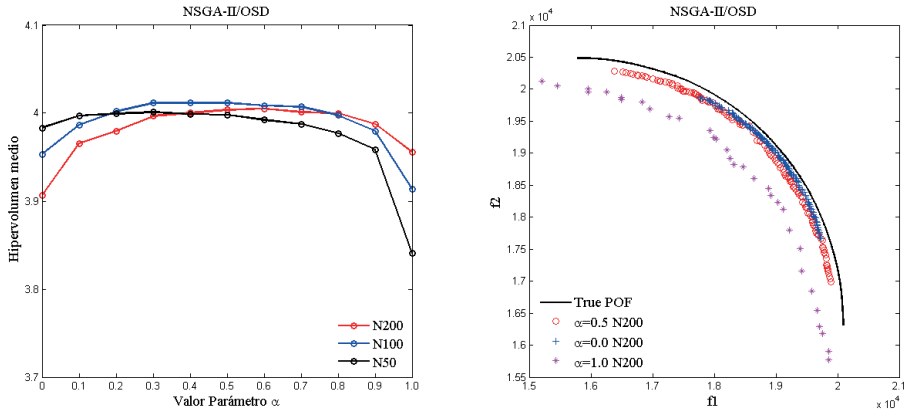

Fig. 3. Valores H al variar el parámetro α (izquierda) y gráficas de soluciones no-dominadas con el valor H más próximo al valor medio final en 30 ejecuciones (derecha).

Además, en la Fig. 4 se muestra la evolución del porcentaje de soluciones diferentes en la población N de soluciones para N=200 y valores α=0.0, α=0.5 y α=1.0. Se observa que el mejor valor porcentaje de soluciones diferentes logrado durante la evolución del algoritmo, se obtiene para α=1.0 lo cual explica la

mejor diversidad (aunque peor convergencia) del POF aproximado alcanzado y mostrado en la Fig. 3 (derecha). También, en la Fig. 4 se aprecia que durante la primera mitad de la evolución del algoritmo, el valor porcentaje de soluciones diferentes en N es mejor cuando se usa el valor α=0.5 en comparación con el valor logrado cuando se utiliza el valor α=0.0, más tarde, hacia el final de la evolución del algoritmo ambos valores se igualan. Esto explica el porqué de la mejor diversidad del POF aproximado alcanzado al final de la evolución y mostrado en la Fig. 3 (derecha), cuando se usa el valor α= 0.5 frente al valor α=0.0.

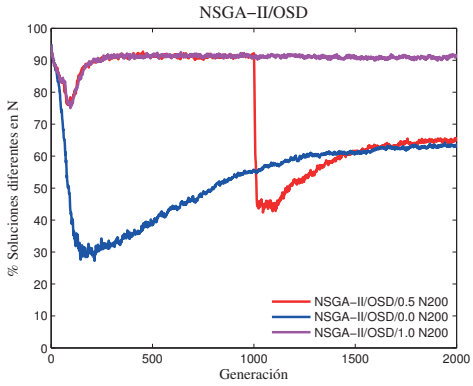

Fig. 4. Evolución de los porcentajes medios de soluciones diferentes en las poblaciones N en el algoritmo propuesto NSGA-II/OSD.

4.4 MOEA/D análisis previo: importancia de la especificación del punto de referencia PR

Dos especificaciones del punto de referencia, la de Zhang y la de Ishibuchi, descritas ambas en los apartados 2.1 y 2.2 se comparan en esta subsección. La Fig. 5 (izquierda) muestra los valores del hipervolumen medio H al variar el valor α en la especificación de Zhang del punto de referencia en MOEA/D según la ecuación (3). El valor H crece hasta un valor máximo (cuando α =1.2) para luego volver a decrecer. También, se puede observar en la Fig. 6 (izquierda) los efectos sobre la diversidad de los frentes de soluciones alcanzados cuando se utilizan los valores α=1.0 (mínima diversidad) y α=1.2 (máxima diversidad y máximo valor de H). Por ello, es altamente recomendable utilizar el valor α=1.2 en MOEA/D cuando se utiliza la versión de Tchebycheff y especificación de Zhang del PR.

Utilizando ahora en MOEA/D la especificación de Ishibuchi del punto de referencia según las ecuaciones (4) y (5) también, al variar el valor α se obtienen diferentes valores del hipervolumen H. La Fig. 5 (derecha) señala que el valor

H crece hasta un valor máximo (cuando $\alpha \geq 3$) a partir del cual permanece estable. Así mismo, se pueden observar, en la Fig. 6 (derecha), los efectos sobre la diversidad y convergencia de los frentes de soluciones alcanzados cuando se usan los valores α=0.0 (mínima diversidad y máxima diversidad), α=10 (máxima diversidad y mínima convergencia) y α=3 (valores de la diversidad y convergencia intermedios). También, en la Fig. 7 se puede ver que al incrementarse el valor α, el porcentaje medio de soluciones diferentes en la población N alcanzado por el algoritmo disminuye. Por lo cual, se recomienda usar el valor α=3.0 en MOEA/D cuando se utiliza la versión de Tchebycheff y especificación de Ishibuchi del PR.

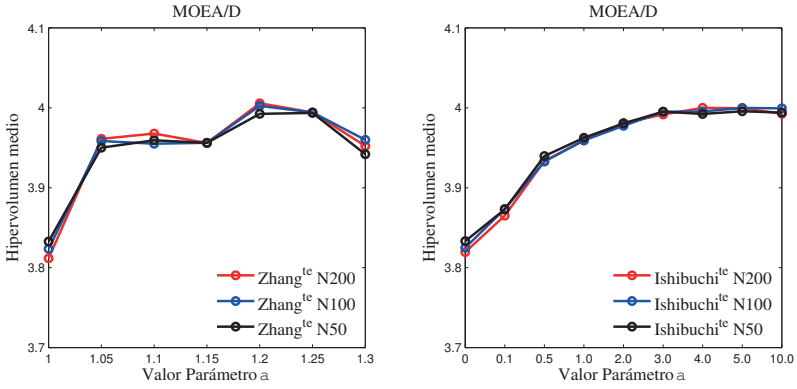

Fig. 5. Valores H al variar el parámetro α en la especificación de Zhang del PR en MOEA/D (izquierda). Valores H al variar el parámetro α en la especificación de Ishibuchi del PR en MOEA/D (derecha).

Por último, en la Fig. 5 (izquierda y derecha) se observa que utilizando las especificaciones de Zhang con el valor α=1.2 e Ishibuchi con valor $\alpha \geq 3$ en MOEA/D (versión Tchebycheff), se obtienen los mejores valores y ambos parecidos según el valor de la métrica H. También, la Fig. 8 muestra similares frentes de soluciones no-dominadas alcanzados por ambos algortimos; no obstante, durante toda la evolución del algoritmo siempre el número de soluciones diferentes en la población N, logrado usando en MOEA/D la especificación de Ishibuchi del PR es inferior al alcanzado utilizando la especificación de Zhang del PR, véase la Fig. 7.

4.5 Resultados comparativos: NSGA-II/OSD vs MOEA/D vs NSGA-II

En esta subsección comparamos el algoritmo NSGA-II/OSD propuesto en este trabajo, con los algoritmos MOEA/D con especificación de Zhang del PR y NSGA-II. Tanto en NSGA-II/OSD como en MOEA/D se utilizó aquel valor α que proporcionó el mejor valor del hipervolumen medio H tras 30 ejecuciones

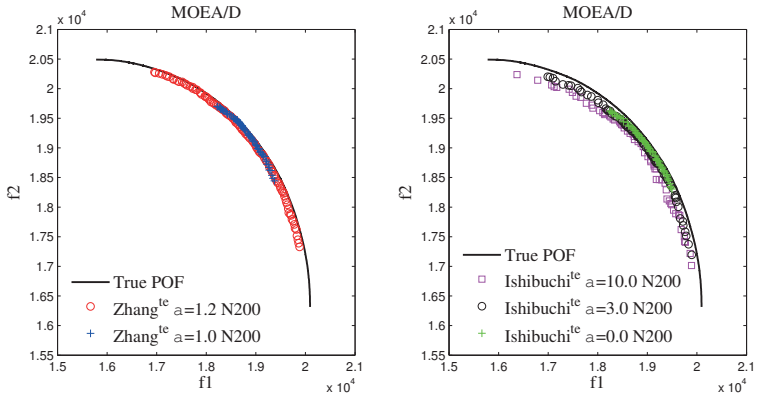

Fig. 6. Gráficas de soluciones no-dominadas con el valor H más próximo al valor medio final en 30 ejecuciones: especificación de Zhang del PR (izquierda), especificación de Ishibuchi del PR (derecha).

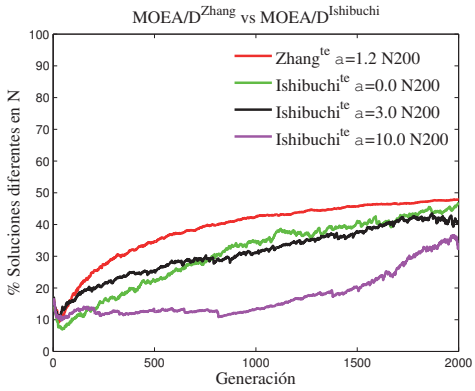

Fig. 7. Evolución de los porcentajes medios de soluciones diferentes en las poblaciones N en el algoritmo MOEA/D utilizando las especificaciones de Zhang e Ishibuchi del PR .

independientes y que según los experimentos descritos en anteriores apartados fueron α=0.5 para NASGA-II/OSD y α=1.2 para MOEA/D.

En la Fig. 9 (izquierda) se muestran los valores del hypervolumen alcanzado por los algoritmos durante su evolución. Se observa en dicha figura, que NSGA-II obtiene siempre el peor valor. Por otro lado, durante la primera mitad de la evolución, MOEA/D consigue un mejor valor de H con respecto al logrado por NSGA-II/OSD; luego, los valores H obtenidos por ambos algoritmos se igualan justo cuando, en las estrategias usadas con NSGA-II/OSD en las regiones R2 y R3 (Fig. 2) se maximizan los dos objetivos del problema. Idéntica conclusión se obtiene con las desviaciones del hipervolumen en la Fig. 9 (derecha).

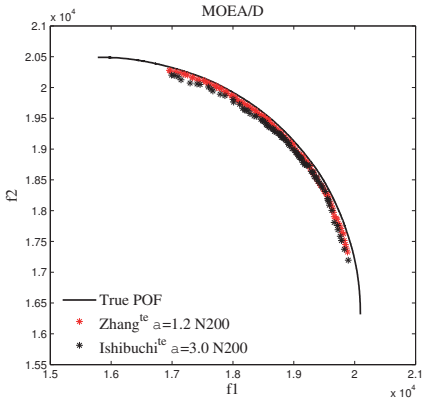

Fig. 8. Gráficas de soluciones no-dominadas con el valor H más próximo al valor medio final en 30 ejecuciones: especificación de Zhang del PR (α=1.2) y especificación de Ishibuchi del PR (α=3.0) .

Por último, en la Fig. 10 se muestran los frentes de soluciones no-dominadas alcanzados por los algoritmos. Se advierte en la figura, que NSGA-II logra una buena convergencia pero muy pobre diversidad de soluciones. Se observa también, que el frente de soluciones alcanzado con el método propuesto obtiene mayor diversidad que la alcanzada por MOEA/D con especificación de Zhang del PR, aunque en términos de convergencia es MOEA/D quien parece tener mejor valor. Estas diferencias, podrían explicarse por la diferencia del valor porcentaje de soluciones diferentes en la poblacion N logrado por los algoritmos durante sus evoluciones, véase la Fig. 11.

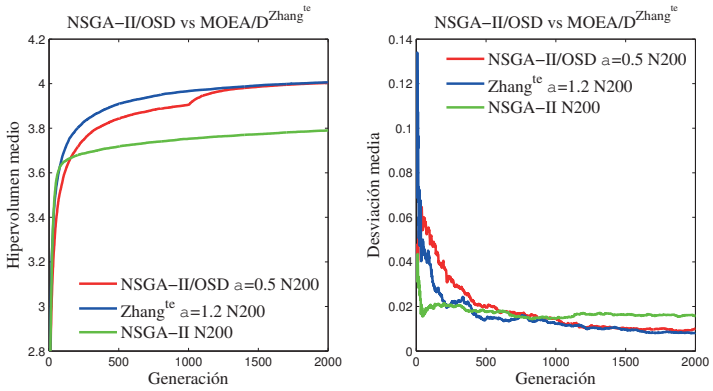

Fig. 9. NSGA-II/OSD versus MOEA/D versus NSGA-II: Evolución de los valores de los hipervolumenes medio (iquierda) y desviaciones del hipervolumen (derecha).

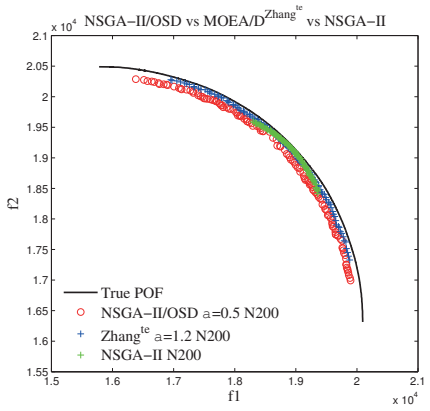

Fig. 10. NSGA-II/OSD versus MOEA/D versus NSGA-II: gráficas de soluciones no-dominadas con el valor H más próximo al valor medio final en 30 ejecuciones.

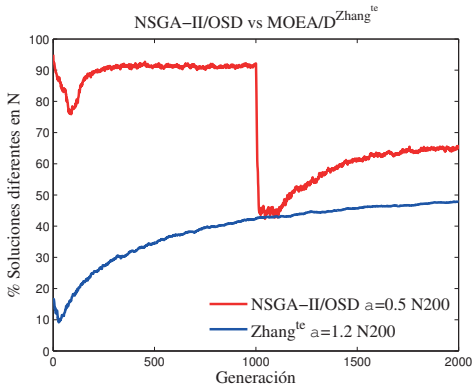

Fig. 11. NSGA-II/OSD versus MOEA/D: Evolución de los porcentajes medios de soluciones diferentes en las poblaciones N.

5 Conclusiones

En este trabajo se propone un algoritmo evolutivo multiobjetivo (NSGA-II/OSD) que hibridiza NSGA-II. El algoritmo subdivide el espacio de los objetivos en varias regiones utilizando la solución Nadir calculada en cada generación del algoritmo. Las distintas subdivisiones utilizan diferentes estrategias de optimización de las funciones objetivo. El algoritmo NSGA-II/OSD propuesto permite definir

un parámetro $\alpha \in [0, 1]$ muy fácil de usar, que permite balancear la diversidad/convergencia del frente de soluciones no-dominadas alcanzado por el algoritmo; para el valor α=0.5 el algoritmo logra su mejor valor de hipervolumen medio.

El algoritmo propuesto obtiene muy buen desempeño y mejores resultados cuando es comparado con NSGA-II. Cuando NSGA-II/OSD es comparado con MOEA/D con la especificación de Zhang del punto de referencia, en términos de la métrica del hipervolumen medio, ambos algoritmos obtienen valores similares. No obstante, NSGA-II/OSD logra una mayor diversificación de soluciones en el frente no-dominado final alcanzado, mientras MOEA/D parece alcanzar mejor convergencia.

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Redes neuronales LSTM aplicadas a la predicción de oleaje en tiempo real para generación de energía undimotriz en las Islas Canarias

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Resumen En las Islas Canarias (España), región ultraperiférica de la Comunidad Europea, la explotación de las energías renovables, como viento, oleaje y sol, proporciona una mayor independencia energética. Para ello es necesario desarrollar modelos de predicción que optimicen el aprovechamiento de dichos recursos. Específicamente, con sistemas de energía undimotriz, la eficiencia de los mismos requiere del conocimiento futuro de las olas incidentes. Con este propósito, se propone en este trabajo la utilización de herramientas basadas en Deep Learning. Además, para la validación de la propuesta, se realiza una comparación de rendimientos entre modelos predictivos basados en redes neuronales recurrentes, concretamente una extensión de estas denominadas LSTM (Long Short Term Memory), y un modelo de predicción autorregresivo cuyos parámetros se calculan utilizando las ecuaciones de Yule-Walker. Se han utilizado dos series temporales de datos de oleaje con distintas características. Para evaluar la eficiencia de los modelos propuestos se ha utilizado el error cuadrático medio, obteniendo los mejores resultados con la red Vanilla LSTM.

Palabras clave: Deep Learning, Red Neuronal Recurrente (RNN), LSTM, Modelos Autorregresivos, Yule-Walker, Predicción de Oleaje

1 Introducción

En regiones insulares como las Islas Canarias (España), con sistemas eléctricos aislados, el aprovechamiento de recursos renovables como viento, oleaje y sol, disponibles en cantidades suficientes [1], contribuye a una mayor independencia energética. Esto se traduce en un menor consumo de combustibles fósiles, menor coste de la energía y menor huella de carbono.

En el año 2018, las Islas Canarias tenían una potencia total instalada de 3.308,6 MW dependiente de hidrocarburos y sus derivados, mientras que sólo

el 13,6% del total, unos 612,3 MW, se correspondían con fuentes de generación renovables [2]. Con esta situación de dependencia, el coste medio de la energía se situó en los 151,71 €/MWh [2]. Por otro lado, el coste de la energía eólica offshore aún no explotada lo suficiente y que requiere de estructuras flotantes para superar las difíciles batimetrías insulares, estaba entre los 82 y los 236 €/MWh [3], dependiendo de parámetros relevantes como la profundidad y la distancia a costa. De igual forma, el coste de la energía undimotriz aún en una fase muy prematura de desarrollo, se calculaba entre los 330-630 €/MWh [4] lo que la hacen económicamente inviable por ahora.

Un presumible descenso futuro de los costes de la energía eólica offshore y su instalación conjunta en plataformas híbridas eólica-undimotriz, con un menor coste medio conjunto al disponer éstas de una única infraestructura flotante así como compartir una única línea de evacuación de energía y mejorar la gestión de los recursos y sus variaciones [5], podrían situar el coste de la energía undimotriz entre los 113 y los 226 €/MWh para el año 2030 [4]. Ello originaría que la energía undimotriz fuese competitiva y pudiese formar parte de los sistemas de generación de energía en las Islas Canarias.

La energía undimotriz, de interés en este trabajo, es un recurso renovable y sostenible que aprovecha a través de sistemas convertidores de energía de las olas (WEC siglas en inglés), la energía contenida en el movimiento de las olas para la generación de energía eléctrica. Debido a las restricciones de diseño que imponen estos tipos de sistemas, el conocimiento y predicción del oleaje son de gran importancia [5], [6], [7]; además, su rendimiento energético puede incrementarse significativamente por ejemplo, mediante sistemas de control que permitan la entrada en resonancia de los dispositivos con el oleaje [8], [9]. No obstante, la predicción de oleaje no es trivial debido a la naturaleza del propio recurso y su comportamiento estocástico.

La predicción de oleaje se ha abordado con diferentes metodologías, entre ellas por ejemplo las que tratan de predecir la altura de ola significativa [9], [10]. En este trabajo se presenta un sistema de predicción de la altura de las olas en tiempo real y se comparan un modelo basado en redes neuronales con otro autorregresivo. El propósito es optimizar la generación de energía de las olas. Para ello, por un lado se entrenará una red neuronal recurrente (RNN siglas en inglés), las cuales han demostrado un rendimiento más general, flexible y adaptable que otros estimadores deterministas [11]. En particular se usarán redes Long Short Term Memory (LSTM siglas en inglés) muy atractivas, pues han evidenciado gran efectividad en aplicaciones con datos secuenciales. Esta metodología por otro lado, se compara con un modelo autorregresivo que utiliza las ecuaciones de Yule-Walker en el ajuste de parámetros.

El resto del trabajo se organiza de la siguiente manera. En la sección 2 se describen los datos y filtrado usados en este trabajo. La sección 3 presenta algunos conceptos básicos de redes neuronales LSTM y modelos de predicción autorregresivos. Los resultados experimentales se detallan en la sección 4. Por último, en la sección 5 se presentan las conclusiones.

2 Datos disponibles

El estudio de la predicción de oleaje se localiza en la isla de Gran Canaria (Islas Canarias), cuya situación geográfica es adecuada desde el punto de vista del aprovechamiento energético undimotriz [12].

La Isla de Gran Canaria ofrece un recurso undimotriz que se sitúa entre los 25 y 30 kW/m [13], inferior a emplazamientos de la costa Europea Atlántica pero igualmente significativo para su explotación. La mayor concentración de energía de las olas se sitúa en alturas entre los 1.5 m y los 3.5 m y períodos de entre 7 s y 13 s [14].

Los datos empleados provienen de observaciones reales provistas por la boya de medición Triaxys Las Palmas Este, operada por el organismo estatal Puertos del Estado cuyo identificativo es 1414, y está situada aproximadamente a 28.05° N y 15.39° W, sobre una profundidad de 30 metros, en la vertiente oriental de la isla.

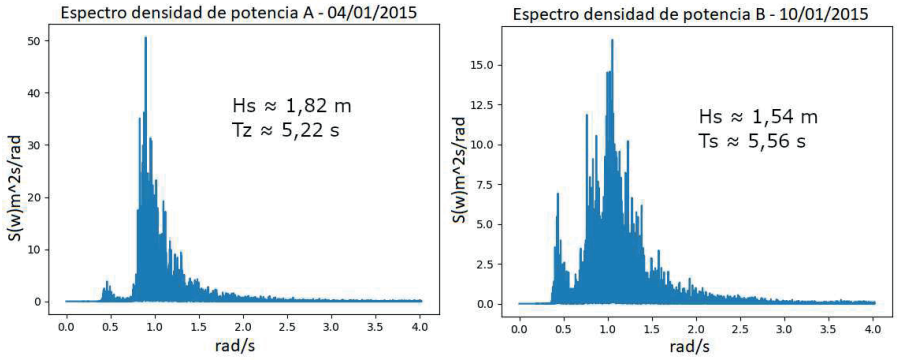

Fig. 1. Espectro del oleaje del conjunto de datos de la muestra: A) 4 de enero de 2015; B) 10 de enero de 2015.

La boya cuenta con una frecuencia de muestreo de 8.04 rad/s (1.28 Hz) Toma datos cada 0.78 segundos, en intervalos de 20 minutos cada hora de medición. Los dos sets de muestras con los que se cuentan pertenecen a los datos recogidos por la boya de medición los días 4 de enero, entre las 11:00 h y las 23:00 h (A), y 10 de enero del año 2015, entre las 00:00 h y las 11:00 h (B), para contar con muestras disímiles, en días y horarios alternos, con la intención de disponer de distintos espectros de oleaje. En total contamos con 36.267 mediciones en el conjunto de datos A, y 41.448 para el conjunto de datos B. Estos espectros de oleaje se representan en la Fig. 1, mostrando diferencias notables. No obstante, aunque ambos espectros están caracterizados por olas de baja frecuencia, en el conjunto de datos B se observa como existe una mayor componente de oleaje de alta frecuencia, lo que nos permitirá validar los modelos de predicción en dos situaciones dispares.

La principal característica que se obtiene del análisis de los datos (Fig. 1), es que gran parte de la energía contenida en las olas se concentra a bajas frecuencias, las cuales son más regulares y están menos afectadas por la no-linealidad [9]. De esta manera, se puede asumir una linealidad entre los valores pasados y futuros de oleaje, pues estos están estrechamente correlados con los posteriores y contienen una menor cantidad de ruido blanco en ellos.

2.1 Filtrado de datos

Estudios previos han demostrado la eficacia de realizar un filtrado a los datos de oleaje [9]. El filtro permite la eliminación de olas de alta frecuencia debidas a la acción localizada del viento y con muy baja energía, por lo que no interesa su predicción desde el punto de vista de un WEC. Por esta razón, a los datos disponibles, conjunto de datos A y B, se les aplicará un filtro de paso bajo de 0.4 Hz, frecuencia estimada como la más idónea para el estudio. La frecuencia de corte y sus implicaciones en el estudio del filtrado de los datos, están fuera del alcance de este trabajo.

3 Modelos de predicción

El objetivo del presente estudio es comparar los resultados obtenidos de una predicción de oleaje cuando se calculan con herramientas basadas en Deep Learning o de manera determinista. Para ello se compararon los resultados obtenidos del modelo mediante el uso de redes neuronales recurrentes (RNN), con los obtenidos utilizando un modelo autorregresivo aplicando el estimador Yule-Walker (YW).

3.1 RNN (LSTM)

Las redes LSTM constituyen un grupo dentro de las redes neuronales recurrentes (RNN), cuya aplicación principal es el procesamiento y predicción de datos dispuestos en secuencias y resultan adecuadas para aprender dependencias a largo plazo [15]. Por tanto, secuencias y dependencias como las que se disponen en una serie temporal de oleaje se prestan a ser modeladas con esta herramienta.

Una característica interesante que presenta una ventaja significativa sobre las redes neuronales tradicionales, es que la arquitectura de la red LSTM (Fig. 2) contiene una puerta de olvido (forget gate) e interconexión entre celdas, que les permite guardar información para procesarla posteriormente (para otras capas, otros inputs, con los que colaboran en la predicción de valores futuros), evitando así que las señales más antiguas se desvanezcan gradualmente durante el procesamiento (vanishing gradient). Esto les confiere un buen rendimiento en la predicción de series temporales, incluyendo el caso particular de las series de oleaje, como así se demuestra en los trabajos de Fan [10] y Hua [16].

En la Fig. 2 se muestra una red LSTM con los diferentes bloques dispuestos a modo de red conectada de forma recurrente. Los bloques contienen módulos

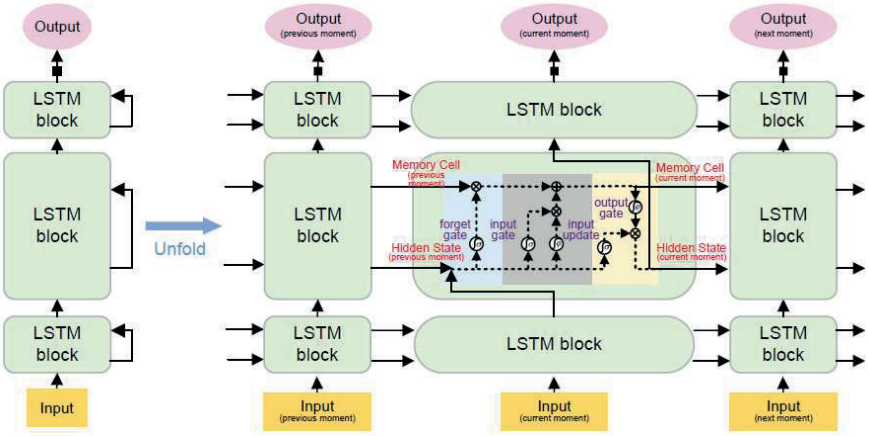

Fig. 2. Red LSTM de tres capas, que muestran las diferentes entradas y el flujo recurrente del que adquieren el nombre estas estructuras [16].

funcionales conformados por las celdas de memoria y sus respectivas puertas. Cada celda de memoria se encarga de recordar el estado temporal de la red neuronal y las puertas formadas por unidades multiplicativas son responsables de controlar el patrón del flujo de información [15].

Según las funcionalidades prácticas correspondientes, estas puertas se clasifican como la puerta de entrada, la puerta de salida y la puerta de olvido. Las puertas de entrada controlan la cantidad de novedad, información nueva que se transmite, es la información que fluye hacia la celda de memoria, mientras que la puerta de olvido gobierna la cantidad de información de la celda de memoria que aún permanece en la celda de memoria actual a través de la conexión recurrente. Por último, la puerta de salida determina cuánta información se usa para calcular la activación de salida del bloque de memoria [15].

Además de la configuración que se muestra en la Fig. 2, correspondiente a la configuración apilada o Stacked LSTM, se pueden disponer de arquitecturas de redes LSTM de manera diferente, con lo que se tendrían tres tipos que son Vanilla LSTM (V-LSTM), Stacked LSTM (S-LSTM), arriba citada, y Bidirectional LSTM (B-LSTM).

Una V-LSTM es un modelo LSTM que tiene una sola capa de unidades LSTM y una capa de salida utilizada para hacer las predicciones. En cambio, una LSTM apilada o S-LSTM se puede definir como un modelo LSTM compuesto por múltiples capas LSTM interconectadas (Fig. 2). Por último, las B-LSTM son aquellas que aprenden la secuencia de entrada hacia adelante y hacia atrás y concatena ambas interpretaciones. De esta forma, la capa de salida puede obtener información de estados pasados (hacia atrás) y futuros (hacia adelante) simultáneamente.

Las diferentes configuraciones no son más que diferentes interconexiones entre los bloques de celdas. Las conexiones entre bloques permiten que una deter-

Tabla 1. Resumen de las especificaciones adoptadas para cada una de los diferentes modelos V-LSTM, S-LSTM, B-LSTM y YW

Modelo	Características
V-LSTM	input layer = 32, lstm_1 layer = 32, output layer = 1 learning rate = 0.001, loss = error cuadrático medio optimizador = adam, epochs = 20, batch size = 70
S-LSTM	input layer = 32, lstm_1 layer = 32, lstm_2 layer = 32 output layer = 1, learning rate = 0.001, loss = error cuadrático medio optimizador = adam, epochs = 20, batch size = 70
B-LSTM	input layer = 32, lstm_bidirectional layer = 64, output layer = 1 learning rate = 0.001, loss = error cuadrático medio optimizador = adam, epochs = 20, batch size = 70
YW	input = 32, coeficientes = 33, output = 1

minada salida conforme inmediatamente el resultado, o sirva de entrada para el siguiente bloque. En nuestro estudio se analizarán las tres configuraciones, para obtener cuál de ellas puede ser más competitiva a la hora de realizar las predicciones con precisión.

En cualquiera de los casos, cualquiera de las configuraciones LSTM (ver Tabla 1) será de 32, es decir, el número de celdas será de 32, con sus respectivos módulos funcionales (input gate, forget gate, ouput gate), para estimar a partir de los 32 estados de oleaje de mar anteriores el estado siguiente (32 inputs), y con una función de activación del tipo tangencial hiperbólica (tanh) para la celda de salida. Esta configuración nos permitirá realizar una comparación con el modelo autorregresivo de orden 32 con ecuaciones de YW, que igualmente emplea los 32 estados anteriores para predecir el siguiente estado de oleaje (ver Tabla 1). Los parámetros de entrenamiento elegidos para cada una de las configuraciones son:

- Número de iteraciones (denominado epochs o épocas) igual a 20
- Tasa de aprendizaje (learning rate en inglés) de 0.001
- Función de pérdida: se considera el error cuadrático medio (RMSE)
- Algoritmo de optimización: se usa el descenso de gradiente eficiente denominado “adam” [17]
- Tamaño de lote (batch size en ingés) de 70

Con estos parámetros se asegura un buen número de muestras de entrenamiento antes de que se actualicen los parámetros internos del modelo.

3.2 Modelo Autorregresivo

El modelo de predicción determinista elegido es un AR autorregresivo (1), que impone una dependencia lineal entre los valores pasados y futuros. Por lo tanto,

el aumento de la onda de oleaje $\eta(k)$ dependerá de sus n valores pasados, siendo n el orden de modelo,

$$\eta(k) = \sum_{i=1}^{n} a_i \eta(k-i) + \xi(k) \tag{1}$$

donde se ha incluido el término de innovación $\xi(k)$. Con las ecuaciones YW [18] se estiman los parámetros a_i, siendo el término de innovación un ruido blanco con varianza σ^2.

Estacionariedad de la serie de tiempo. En primer lugar, se verificará que se cumplen las hipótesis de que las series de tiempo consideradas son estacionarias. Para ello se aplicarán los test estadísticos ADF (Augmented Dickey–Fuller) [19], [20] y KPSS (Kwiatkowski-Phillips-Schmidt-Shin) [21]. Hay que tener en cuenta que, en el test ADF la hipótesis nula es H0: "la serie temporal es no estacionaria", y en el test KPSS la hipótesis nula es H0: "la serie temporal es estacionaria". Por lo tanto, en el primer caso interesa obtener un p-valor pequeño (menor que 0,05) y en el segundo caso interesa obtener un p-valor no tan pequeño (mayor que 0,05). Realizados los test con los datos considerados en este trabajo (Sección 2), se obtuvo un p-valor inferior a 0,01 con el test ADF y superior a 1,0 con el test KPSS, lo que nos permite suponer que las series temporales son estacionarias.

Yule-Walker. Las ecuaciones YW [18] se usan para estimar los parámetros a_i (inferiores a la unidad y condición de proceso estacionario) que gobiernan el modelo autorregresivo (1), de modo que la mejor predicción con l pasos avanzados desde el instante k, se estima como se muestra en (2).

$$\widehat{\eta}(k+l|k) = \sum_{i=1}^{n} \widehat{a}_i \widehat{\eta}(k+l-i|k) \tag{2}$$

Los parámetros de las ecuaciones de YW se pueden obtener a través de la función de covarianza o a través de la función de correlación (y autocorrelación), que se muestra en (3).

$$Corr[y_t, y_{t-k}] = \frac{E[y_t - \mu][y_{t-k} - \mu]}{E[y_t - \mu]^2} = \frac{y_k}{y_0} = \rho_k \tag{3}$$

Por último, a partir de la función de autocorrelación se pueden estimar los parámetros que definen el modelo. Concretamente, resolviendo el sistema de ecuaciones (4) se calculan los valores de los parámetros a_i que gobiernan el fenómeno, los datos de oleaje, de manera que podamos estimar los valores futuros de la ola incidente con (2). En este caso n = 32, es decir, emplearemos un modelo de orden 32, que ya ha demostrado ser apto para este tipo de aplicaciones [22].

$$\begin{bmatrix} \rho_1 \\ \rho_2 \\ \vdots \\ \rho_{p-1} \\ \rho_p \end{bmatrix} = \begin{bmatrix} 1 & \rho_1 & \cdots & \rho_{p-2} & \rho_{p-1} \\ \rho_1 & 1 & \cdots & \rho_{p-3} & \rho_{p-2} \\ \vdots & & & & \\ \rho_{p-2} & \rho_{p-3} & \cdots & 1 & \rho_1 \\ \rho_{p-1} & \rho_{p-2} & \cdots & \rho_1 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{p-1} \\ a_p \end{bmatrix} \quad (4)$$

4 Experimentos

En esta sección se exponen los resultados alcanzados con los dos modelos de predicción descritos, los basados en las redes LSTM con las diferentes configuraciones y el modelo autorregresivo con ecuaciones de YW. En ambos casos se emplean los 32 estados anteriores para conformar la siguiente predicción (orden del modelo de 32 en el caso del autorregresivo, 32 entradas en el caso de las LSTM) de manera que se equiparen los resultados.

Ambos modelos deben ser entrenados, a fin de obtener los parámetros óptimos que definen el fenómeno. En este punto, el entrenamiento de los modelos ya nos ofrece una primera conclusión, YW no requiere sino de los 32 estados anteriores para entrenarse y de 32 estados siguientes de test. En cambio, con este conjunto de entrenamiento tan limitado, 32 estados, la red LSTM sería incapaz de optimizar los parámetros necesarios. Por tanto, con LSTM, se opta por generar subconjuntos de datos, 5 en concreto, en los que 4 de estos subconjuntos conformarán el conjunto de entrenamiento y el restante será el conjunto de test. Para poder estimar el rendimiento se opta por un proceso de validación cruzada, en las que los subconjuntos se alternan de manera que se obtengan diferentes conjuntos de entrenamiento y test con los mismos subconjuntos. Para las muestras A y B (con filtro), el tamaño de los subconjuntos de entrenamiento es de 28.987 y 33.132 datos y de 8.283 y 7.247 datos, respectivamente, para los subconjuntos de test.

Los primeros resultados que se muestran son los de la red LSTM y las diferentes configuraciones descritas. Se evalúan a través de la raíz del error cuadrático medio (RMSE), la media de los diferentes subconjuntos de datos (folders) derivados de la validación cruzada y su desviación. Los resultados se muestran en la Tabla 2 para el conjunto de datos A, del 4 de enero de 2015, y la Tabla 3 para el conjunto de datos B, del 10 de enero del 2015.

Un análisis de los valores de las Tabla 2 y Tabla 3, indica que la configuración más simple, la V-LSTM, es la que mejores resultados ofrece con ambos conjuntos de datos. También, se observa que con cualquiera de las configuraciones existen diferencias entre los diferentes conjuntos de datos (A y B) en términos de rendimiento, asociado a los diferentes espectros del oleaje existente (ver Fig. 1), por lo que existe una relación entre el rendimiento (RMSE) y el estado del mar existente en cada momento durante las predicciones. Por otro lado, en las figuras (Fig. 3-5) se presentan las funciones de pérdida de las distintas redes LSTM, que muestran una buena optimización (loss bajo) y ausencia de sobreajuste (overfitting), es decir sin diferencia apreciable entre el coeficiente de

Tabla 2. Resultados obtenidos con las diferentes configuraciones LSTM para datos A

Modelo	$RMSE_{medio}$	$RMSE_{std}$	Entrenamiento (s.)		Predicción (s.)	
			T_{medio}	T_{std}	T_{medio}	T_{std}
V-LSTM	10,112	2,460	23,88	3,08	0.017	0,016
S-LSTM	11,456	3,200	31,33	5,29	0,016	0,010
B-LSTM	11,456	3,826	28,19	5,85	0,014	0,011

Tabla 3. Resultados obtenidos con las diferentes configuraciones LSTM para datos B

Modelo	$RMSE_{medio}$	$RMSE_{std}$	Entrenamiento (s.)		Predicción (s.)	
			T_{medio}	T_{std}	T_{medio}	T_{std}
V-LSTM	8,291	1,549	91,39	21,37	0.028	0,002
S-LSTM	9,220	1,297	36,86	10,37	0.016	0,008
B-LSTM	8,830	1,342	30,71	7,010	0.015	0,009

Tabla 4. Resultados obtenidos con el modelo AR - YW

Datos	Modelo	$RMSE_{medio}$	$RMSE_{std}$	Entrenamiento (s.)		Predicción (s.)	
				T_{medio}	T_{std}	T_{medio}	T_{std}
Data set A	YW	11,826	2,955	0,021	0,002	$6{,}04{\cdot}10^{-5}$	$1{,}51{\cdot}10^{-5}$
Data set B	YW	15,847	4,669	0,026	0,008	$7{,}08{\cdot}10^{-5}$	$1{,}78{\cdot}10^{-5}$

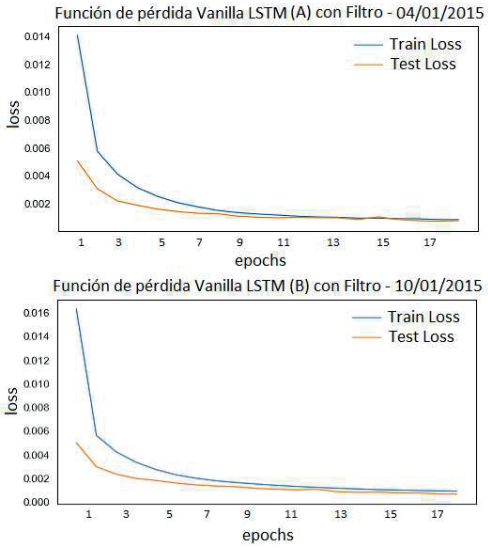

Fig. 3. Función de pérdida para las diferentes epochs (configuración Vanilla), para los conjuntos de datos A (4 de enero de 2015) arriba, y B (10 de enero de 2015) abajo.

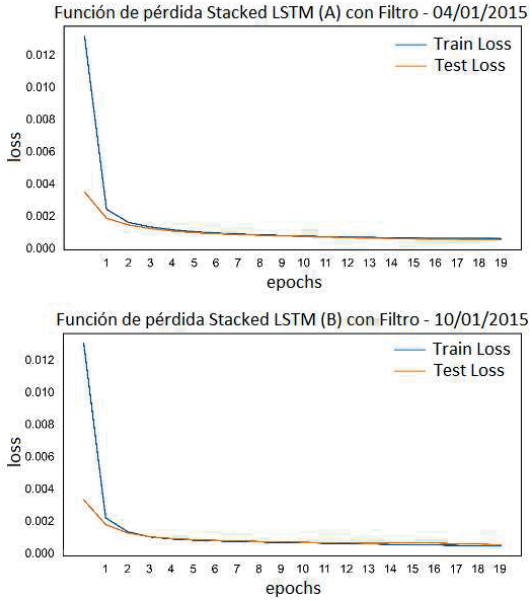

Fig. 4. Función de pérdida para las diferentes epochs (configuración Stacked), para los conjuntos de datos A (4 de enero de 2015) arriba, y B (10 de enero de 2015) abajo.

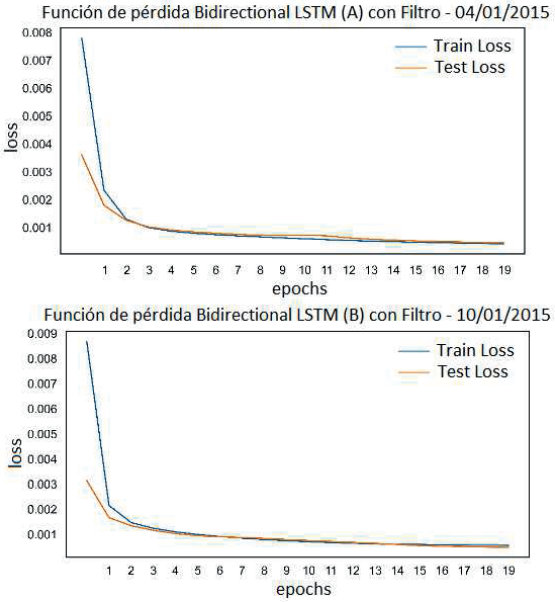

Fig. 5. Función de pérdida para las diferentes epochs (configuración Bidirectional), para los conjuntos de datos A (4 de enero de 2015) arriba, y B (10 de enero de 2015) abajo.

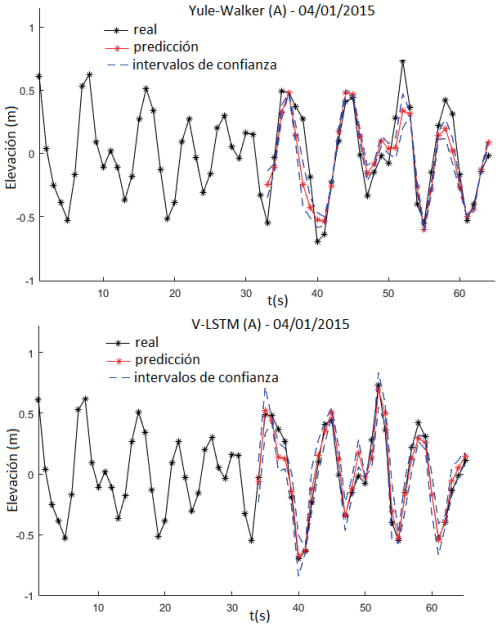

Fig. 6. Resultados gráficos temporales, arriba, Yuler-Walker, abajo, V-LSTM, para el conjunto de datos A.

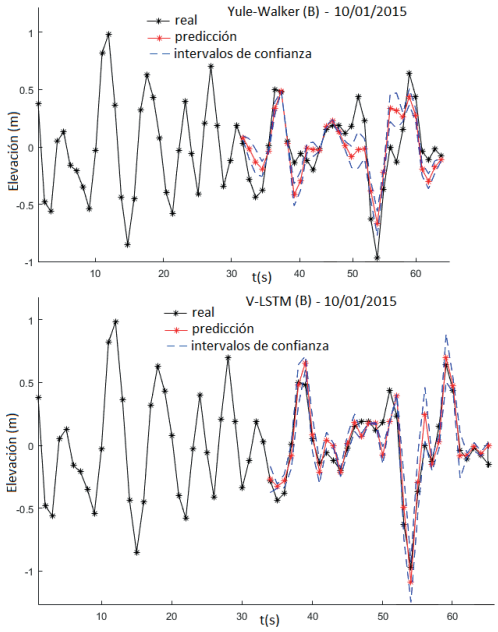

Fig. 7. Resultados gráficos temporales, arriba, Yuler-Walker, abajo, V-LSTM, para el conjunto de datos B.

perdidas (loss) de entrenamiento y el de test. La configuración V-LSTM, que es la más sencilla, requiere de un menor número de parámetros y ha demostrado, frente a las restantes configuraciones un mejor rendimiento y menor complejidad, aún así hablamos de optimizar 8.853 parámetros con la V-LSTM, por los 16.673 y los 16.705 parámetros de las configuraciones S-LSTM y B-LSTM respectivamente, un número elevado si comparamos con los 32 que se deben determinar en el proceso autorregresivo.

En el modelo autorregresivo estimado con las ecuaciones de YW, para igualar las condiciones de predicción del modelo neuronal, se seleccionaron al azar en las muestras de datos A y B, 32 estados de oleaje de mar a modo de entrenamiento, para realizar las siguientes 32 predicciones de manera continuada, con 5 selecciones aleatorias de las que se ha obtenido el error medio y la desviación. En ambos conjuntos de datos el error es superior en el modelo autorregresivo frente al modelo V-LSTM (ver Tablas 2-3-4), esta diferencia también se puede ver gráficamente realizando una predicción temporal (ver Fig. 6-7).

Finalmente, señalar que todas las mediciones de tiempos (entrenamiento y predicción) mostradas en las Tablas 2-3-4 han sido hechas en Intel Core i7-8550U, 1.8-4.0 GHz y 4 núcleos.

5 Conclusiones

En este estudio, se utilizan 3 configuraciones de redes LSTM y un método determinista AR-YW con dos conjuntos A y B de datos de oleaje, recogidos en las Islas Canarias en días dispares, para realizar un modelo predictivo del comportamiento del oleaje en condiciones ambientales oceánicas diferentes. Se utiliza el indicador error cuadrático medio (RMSE), para evaluar la precisión y la estabilidad de los resultados de la predicción alcanzados con los diferentes modelos, a partir de los dos conjuntos de datos.

Los experimentos mostraron que la red V-LSTM puede lograr resultados más precisos, con un menor error y más constantes que otras configuraciones LSTM y que el modelo AR-YW. Por ello la aplicación de redes LSTM es una metodología adecuada para la predicción de oleaje a corto plazo. No obstante, como sistema instalado en un generador undimotriz para predicción en tiempo real presenta algunas dificultades, como por ejemplo el coste computacional, Este se traduce en tiempos de entrenamiento mayores, dada la multitud de parámetros a estimar, 8.853, frente a los 32 utilizados por el modelo autorregresivo. Este mayor coste computacional, no debe ser un impedimento para desestimar las redes LSTM, pues los resultados están a su favor. No obstante, su utilización requiere de una buena estrategia de entrenamiento y predicción que desacople ambos procesos, de manera que el mayor coste no influya en el desarrollo de un sistema de predicción en tiempo real. Esto constituye una línea de trabajo futura.

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Algoritmos genéticos para la toma de decisiones en la cadena de valor apícola

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Resumen
Se ha planteado e implementado un modelo no lineal para optimizar la cadena de valor apícola en el sudoeste bonaerense (Argentina) con el objeto de maximizar el Valor Actual Neto. La propuesta consiste en emplear un Algoritmo Genético anidado cuyo diseño contempla diferentes alternativas en la toma de decisiones. Con el fin de lograr una implementación eficiente, se han adoptado técnicas de programación paralela para explorar diferentes instancias simultáneamente. De esta manera, se logra identificar oportunidades para que la cadena de valor del productor apícola pueda obtener una ventaja competitiva.

Palabras clave: Cadena de Valor, Algoritmo Genético, Productor Apícola.

1 Introducción

El concepto de cadena de valor (CdV) fue desarrollado y popularizado en 1985 por Michael Porter [1], en su libro "Ventaja Competitiva: crear y sostener un desempeño superior". Dicho autor definió el valor como la cantidad que los compradores están dispuestos a pagar por un producto o un servicio que proporciona una empresa, y concibió la CdV como la combinación de nueve actividades estratégicas de valor agregado que operan dentro de una empresa y que trabajan en conjunto para proporcionar valor para los consumidores o usuarios.

A las primeras cinco actividades, Porter [1] las denomina primarias, las cuales se relacionan con la creación física del producto, y su venta y transferencia al comprador, así como la asistencia posterior a la venta (logística interna, operaciones, logística ex-

terna, mercadotecnia, y ventas y servicio). Las restantes cuatro actividades (de infraestructura de la empresa, administración de recursos humanos, desarrollo tecnológico y adquisiciones), Porter las denomina de apoyo, las cuales sustentan a las actividades primarias y se apoyan entre sí, proporcionando insumos comprados, tecnología, recursos humanos y varias funciones de toda la empresa.

Año tras año, el concepto de CdV ha sido objeto de abundante literatura. Siguiendo a Kippenberger [2], se denomina CdV al conjunto de actividades principales de una empresa, que se unen a través de eslabones, y a medida que el producto pasa por cada uno de ellos va añadiendo su valor. Por su parte, Kaplinksy [3], afirma que la CdV hace referencia a todas las actividades para que un producto o servicio, desde su concepción hasta sus distintas fases de producción - pudiendo involucrar distintas combinaciones de transformación física, de insumos y de diferentes servicios -, sea entregado a disposición del usuario o consumidor final y su posterior desecho. A medida que el producto se mueve de una actividad hacia la otra dentro de la CdV, añade valor al producto o servicio final [4].

Como tal, la CdV puede utilizarse como una herramienta para desglosar un negocio en actividades principales, permitiendo así la identificación de fuentes de ventaja competitiva [5]. El análisis de la CdV es un método utilizado para descomponer el conjunto en las actividades que lo conforman, con la finalidad de facilitar la toma de decisiones estratégicas, al ubicar a la empresa frente a sus clientes, proveedores y competidores. Dicho análisis proporciona recomendaciones útiles para ajustar las acciones y los procesos, con el objeto de dar el mayor valor posible al mercado destinatario y aumentar los márgenes de beneficio de la empresa.

La CdV elegida en el presente estudio es la apícola, específicamente la del SO bonaerense (Argentina). La Organización de las Naciones Unidas para la Alimentación y la Agricultura [6] (FAO, según sus siglas en inglés) define a la apicultura como la ciencia y el arte de la cría de abejas. Dicha actividad económica es valorada no sólo por los productos de alto valor biológico y los servicios a la polinización de cultivos, sino también por su contribución al desarrollo regional con generación de empleo rural y por las bajas barreras de entrada, particularmente en el eslabón primario.

Existen buenas razones para defender y preservar la actividad apícola. Por un lado, posee un alto impacto social dado que se trata de un medio de producción de subsistencia para muchas regiones de nuestro país, en las que los ingresos provienen de las exportaciones de miel que movilizan en parte la actividad comercial. Por otro lado, y no menos importante, la necesidad de contar con poblaciones importantes de insectos polinizadores, indispensables para la producción agrícola y la ecología local.

Adicionalmente, el sistema de valor apícola está conformado por diversas CdV, tales como la del productor apícola, las salas de extracción, los acopiadores, los fraccionadores, los exportadores, los productores de materiales e insumos y los oferentes de servicios técnicos especializados, y diversos subproductos de la colmena, como polen, jalea real, propóleos, apitoxina, cera, material vivo, entre otros. La apicultura, en su sentido amplio, aporta a la economía y a la sociedad mucho más que miel, y quizás en esas externalidades radiquen parte de los desafíos más relevantes del sector apícola argentino.

Si bien, de acuerdo al Ministerio de Agricultura, Ganadería y Pesca de la Nación [7], gran parte del territorio argentino es apto para el desarrollo de la actividad y presenta distintos potenciales productivos tanto para la miel como para los subproductos de la colmena, Buenos Aires es la provincia con mayor concentración de la producción. La misma cuenta con alrededor de 915 mil colmenas, según fuentes oficiales de la Secretaría de Agroindustria de la Nación, seguida por la provincia de Entre Ríos, con 572 mil colmenas, Santa Fe, con unas 295, Córdoba con números similares y La Pampa, con cerca de 208 mil colmenas.

A pesar de que Porter [8] conectó las CdV entre empresas para formar lo que llamó "sistema de valor", para el presente estudio se utiliza el concepto de CdV del eslabón primario del sistema mayor, es decir, de los productores apícolas, sin analizar el sistema de valor apícola en su conjunto. Esto abre una futura línea de investigación.

El objetivo de este estudio consiste en determinar las principales actividades que crean valor para los consumidores finales o clientes y las actividades de apoyo relacionadas de la CdV del productor apícola del sudoeste (SO) bonaerense. Para ello, se emplea un optimizador que permite contemplar las no linealidades subyacentes en los modelos económicos, de modo de servir como soporte de la toma de decisiones del productor con el fin de detectar oportunidades, que puedan crear una ventaja competitiva.

2 Modelo matemático de la cadena de valor apícola

2.1 Descripción de la cadena de valor apícola

Para realizar el presente estudio se utiliza como referencia la zona del sudoeste bonaerense (Argentina). Según los Fundamentos de la Ley del Sudoeste Bonaerense (LP 13.647), esta región representa aproximadamente el 25% del territorio de la provincia de Buenos Aires. No es pampa húmeda, sino que forma parte de las regiones semiárida, árida y subhúmeda-seca del país, con características climáticas y edáficas que la diferencian del resto de la provincia en cuanto a sus potencialidades y limitantes productivas primarias, y por lo tanto también, en cuanto a las ventajas comparativas, claramente inferiores al resto de la provincia. Esta cuenca melífera está integrada por los partidos de Guaminí, Adolfo Alsina, Coronel Suarez, Coronel Pringles, Coronel Dorrego, Saavedra, Tornquist, Puán, Coronel Rosales, Bahía Blanca, Villarino y Patagones.

La región nombrada en el párrafo precedente posee una característica diferencial: contiene a todos los actores del sistema de valor apícola, desde productores a comercializadores, desde servicios técnicos hasta provisión de insumos, desde operadores logísticos hasta entes de financiamiento, entre otros.

De acuerdo a Goslino (2017) [10], debido a que el sudoeste bonaerense continúa siendo una zona agrícolamente marginal, con orientación ganadera y por ende pastizales naturales y montes, el potencial apícola supera largamente a otras regiones del país (particularmente la zona núcleo, en la pampa húmeda) donde la intensa agriculturización y el uso de agroquímicos dificultan cada vez más la continuidad de la apicultura.

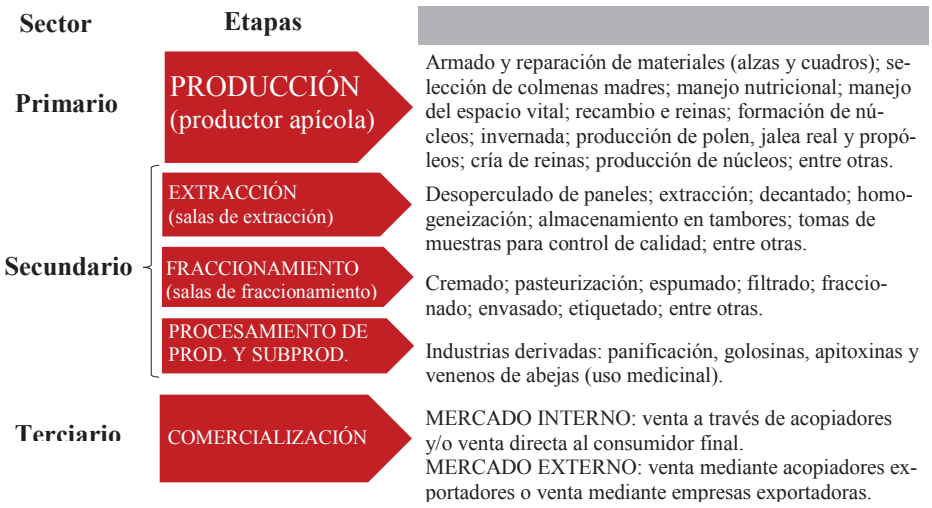

Fig. 1. Sistema de valor apícola.

Respecto al valor de los costos en los que incurre el apicultor, ya sean los directos de una actividad específica o los costos indirectos, son impuestos por los proveedores de insumos, las salas de extracción y las de fraccionamiento. En cuanto a los precios de venta, el productor apícola ofrece los productos y subproductos de su actividad a un precio fijado por el mercado, por ende, se lo considera tomador de precios. A efectos de este trabajo, se asume que el apicultor vende la miel a un precio único, ya sea al mercado destinatario interno o externo. En un entorno cambiante, la estructura de un proyecto apícola puede diseñarse teniendo en cuenta varias alternativas. En el modelo de CdV implementado en este trabajo, se han considerado únicamente las actividades estacionales resumidas en la Tabla 1.

Tabla 1. Actividades estacionales en la apicultura.

Actividad	Primavera (I)	Verano (II)	Otoño (III)	Invierno (IV)
Mantenimiento	☑	☑	☑	☑
Cosecha miel		☑		
Venta		Núcleos	Miel	
Producción de núcleos	☑			

En este trabajo únicamente se describe la primera etapa de desarrollo, que comprende la formulación e implementación del modelo matemático preliminar, la implementación del algoritmo genético anidado arriba descripto y los testeos necesarios. Por lo tanto, por razones de simplicidad, no se incluyen algunas actividades usuales ni ciertas variables pertinentes (p.ej. impuestos, regalías, entre otros) que complican el programa computacional. En la segunda etapa de desarrollo, se planifica incorporar términos que

contemplen otras actividades usuales, tales como los servicios de polinización y la redistribución de colmenas durante el invierno. Cabe destacar que en etapas posteriores deberán incluirse todas las variables relevantes y también las interrelaciones entre ellas expresadas en términos matemáticos. Así, esto permitirá que el modelo final sea realista, aunque dará lugar a un modelo matemáticamente más complicado.

3 Función objetivo

La función objetivo propuesta (Ec. 1) maximiza el valor actual neto (VAN) de las diversas actividades que componen la cadena de valor de la actividad apícola. El VAN se calcula como la suma de la inversión inicial I_0 y la sumatoria de la corriente de ingresos y gastos de las diversas actividades llevadas a cabo en las cuatro estaciones del año. A dicha sumatoria se la debe actualizar a la tasa anual de interés i_A, donde $y \in Y$ es uno de los años del horizonte temporal a evaluar.

$$VAN = -I_0 + \sum_{y=1}^{Y} (Invierno + Primavera + Verano + Otoño)(1 + i_A)^{1-y} \quad (1)$$

Las variables de decisión de este problema son el número y la disposición de las colmenas en cada campo $c \in C$ para cada año y $X_{y,c}$, y si produce material vivo para la venta $MV_{y,c}$. La inversión inicial I_0 consiste en el conjunto de bienes de capital necesarios para iniciar la actividad, tales como las herramientas de trabajo, el material vivo inicial, las colmenas y el vehículo para movilizarse entre los distintos campos. Eventualmente, algunos materiales deberán ser reemplazados, actualizándose en dicho momento a la tasa i_A.

Los flujos de ingresos y gastos de la actividad son eminentemente estacionales, y dichos montos se encuentran actualizados a la tasa cuatrimestral i_e. En el invierno, para la producción de miel, sólo se afrontan los costos indirectos asociados a la actividad de mantenimiento de las colmenas de dicha estación. En cambio, en dicha estación, para la producción de núcleos, comienza el período de una estimulación extra en la alimentación de las colmenas con el fin prepararlas para la reproducción, por lo que comienzan las erogaciones vinculadas a la producción de material vivo. En primavera, se originan las primeras erogaciones vinculadas a la producción miel y, sobre finales de dicha estación, las erogaciones de alimentación extra para producir material vivo finalizan. Luego, el valor actual de los ingresos y gastos en verano está conformado por la sumatoria actualizada de los ingresos por la venta de material vivo y de los costos de producción de miel. Las utilidades obtenidas en la estación otoño provienen de los ingresos por la venta de miel. En todas las estaciones el apicultor debe solventar gastos relacionados al mantenimiento de las colmenas $Mant_{y,c}^{e}$ (Ec. 2). Estos costos están mayormente relacionados a la mano de obra $ManoObra_{y,c}^{e}$, a la movilidad entre campos $Movilidad_{y,c}^{e}$ y a la alimentación de las abejas $CostoAzucar_{y}^{e}$, cuya cuantía varía según la época del año y la actividad llevada a cabo.

$$Mant_{y,c}^{e} = X_{y,c}\left(ManoObra_{y,c}^{e} + Movilidad_{y,c}^{e} + CostoAzucar_{y}^{e}\right) \quad \forall\, c = 1, C \quad (2)$$

Si el productor decide elaborar material vivo, esta actividad comienza al terminar el invierno y finaliza a fines de la primavera, aunque sus costos se erogan durante todo el año. La decisión de llevar a cabo esta actividad es registrada mediante la variable de decisión binaria $MV_{y,c}$, la cual toma valor unitario en el caso de que se decida llevar a cabo dicha actividad en el campo c durante el año y. El costo de producir el material vivo $CostoMV^e_{y,c}$ (Ec. 3) está vinculado a la mano de obra especializada ($ManoObraMV^e_{y,c}$) y a la alimentación adicional $CostoAzucarMV^e_y$ para las colmenas que se reserven para esta actividad N_y.

$$CostoMV^e_{y,c} = MV_{y,c}\ (N_y\ CostoAzucarMV^e_y + ManoObraMV^e_{y,c}) \qquad \forall\ y = 1, Y \text{ (3)}$$

El ingreso de esta actividad $InMV_{y,c}$ puede calcularse como la diferencia entre el precio de venta de cada núcleo $PrecioMV_y$ y los insumos necesarios para la venta $CostoMV_{y,c}$, multiplicado por la cantidad de núcleos producidos $ProdNucleos_{y,c}$ por las colmenas dedicadas a tal fin N_y.

$$InMV_{y,c} = MV_{y,c}\ N_y\ ProdNucleos_{y,c}\left(PrecioMV_y - CostoMV_{y,c}\right) \quad \forall\ y = 1, Y \text{ (4)}$$

La venta de miel en otoño está representada en la Ec. 5, calculada a través del producto entre la cantidad producida de miel $ProdMiel_{y,c}$ (en kg/colmena en función de cada campo); la cantidad de colmenas en cada campo $X_{y,c}$; y el margen bruto por kg. de miel. Este último viene dado por la diferencia entre el precio $PrecioM_y$ y los costos de venta por kg de miel $CostoM_{y,c}$.

$$VentaMiel = \sum_{c=1}^{C} X_{y,c}\ ProdMiel_{y,c}\ (PrecioM_y - CostoM_{y,c}) \quad \forall\ y = 1, Y \text{ (5)}$$

La variable de decisión asociada a la distribución de colmenas $X_{y,c}$ enfrenta restricciones referidas a la capacidad máxima de albergue de cada campo $XMax_{y,c}$ (Ec. 6) y al crecimiento del colmenar. El aumento del número de colmenas totales viene dado por una función f, eventualmente ni lineal ni derivable, que describe tanto el incremento natural como la incorporación y posible venta del stock productivo (Ec. 7).

$$X_{y,c} \leq XMax_{y,c} \qquad \forall\ c = 1, C; y = 1, Y \text{ (6)}$$

$$X_{y,c} = f(X_{y-1,c}) \quad \forall\ y = 1, Y \text{ (7)}$$

El apicultor comienza con un stock inicial X_0 (Ec. 8), cuya ubicación en las localizaciones alternativas se restringe por la cota máxima descripta anteriormente y una cota mínima $XMin$ (Ec. 9) que garantiza una escala de trabajo rentable por cada localización.

$$\sum_{c=1}^{C} X_{0,c} = X_0 \text{ (8)}$$

$$X_{y,c} \geq XMin \quad \forall\ y = 1, Y \text{ (9)}$$

Luego del primer año, el apicultor puede enfrentarse a la necesidad de mover colmenas entre campos. Debido a este esfuerzo, el costo de mudanza (Ec. 10) depende de la diferencia entre la cantidad real de unidades en un campo y la cantidad que debería haber según la función de crecimiento f aplicada sobre la cantidad del año anterior. Si esta magnitud supera las 25 colmenas, es valuada considerando el costo por colmena $CMud_y$.

$$CostoMud_{y,c} = \left[f\left(X_{y-1,c}\right)X_{y-1,c} - X_{y,c}\right] CMud_y \quad \forall\, y = 2, Y \tag{10}$$

4 Metodología

Hemos diseñado e implementado un modelo de cómputo paralelo en el cual varios hilos de procesamiento optimizan simultáneamente diversos escenarios que han sido definidos por un algoritmo Maestro (Master). Como los resultados provenientes de los Trabajadores (Workers) serán diferentes, el Maestro ordena las soluciones candidatas según su aptitud y sincroniza la operación de los procesadores, asignándole a cada uno desocupado otro escenario prometedor a resolver. Este método involucra la búsqueda de la solución de muchos subproblemas de optimización simples, de pequeña dimensión, en lugar del problema original. Cuando está disponible un sistema de cómputo paralelo, este método se vuelve mucho más atractivo porque los subproblemas simples pueden resolverse de manera simultánea.

Según el presente enfoque de búsqueda iterativa, la Fig. 2 muestra un diagrama de flujo de dicho optimizador con la estructura Master (1) -Workers (2). Para simplificar esta explicación, asumimos que hay K Trabajadores disponibles (k=1,2,…K). Cuando se introducen los datos para un problema de optimización, en la Estrategia de Búsqueda (1) el Maestro crea K individuos, los cuales tienen definidos diferentes parámetros en sus respectivos cromosomas. El Maestro reparte los individuos entre los trabajadores y cada uno se encarga de la Búsqueda de una Solución (2) de acuerdo a lo que el Maestro ha decidido en su Estrategia (1). Mediante la técnica de Algoritmos Genéticos (AG) [9], cada Trabajador (2) genera la población inicial correspondiente tomando como base el individuo patrón que le fue asignado y aplica los procesos de selección, cruzamiento y mutación, produciendo así nuevos individuos de la próxima generación. Así se producen un grupo de Soluciones Candidatas (4) independientemente, basadas en los diferentes tipos de individuos (3).

El Maestro (1) recibe información sobre las Soluciones Candidatas (4) y los valores correspondientes a su fitness, reordenándolas con un ranking de aptitud. Cuando es necesario buscar los candidatos de la próxima generación, la optimización de la Estrategia de Búsqueda (1) decide los individuos patrón (3) para la próxima Búsqueda (2). Si no hay necesidad de tomar más decisiones, el Maestro elige la Solución del candidato más apto como la Solución final del problema original de optimización. Aunque esta solución final, no es la solución óptima exacta en un sentido estricto en la mayoría de los casos, es simplemente una solución aceptable, que muestra un valor de idoneidad relativamente excelente dentro de un rango predeterminado.

En vez de aplicar representaciones tradicionales de los individuos del AG, todos los parámetros correspondientes a la toma de decisiones y todas las variables de optimización se representan juntos para conformar un único cromosoma. Por ende, nuestra propuesta emplea una estructura genética tal como se muestra en la Fig. 3. Para el k-ésimo individuo, la primera parte TD_k, referida a la toma de decisiones, tiene exclusivamente elementos binarios; mientras que el resto VO_k consta de genes que en este caso corresponden a números enteros. Esta estructura nos ha incentivado a definir estrategias especiales para los operadores genéticos.

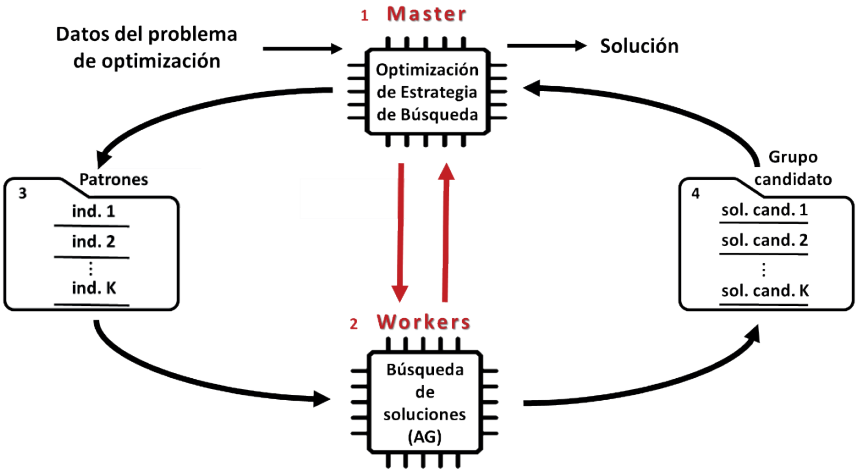

Fig. 2. Representación conceptual del optimizador.

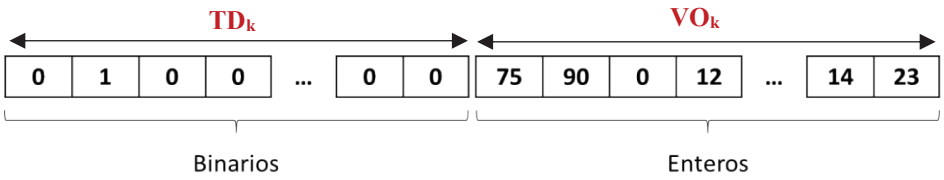

Fig. 3. Ejemplo de estructura genética del k-ésimo individuo.

El desafío que plantea un problema de optimización dinámico es la correlación temporal de las variables de decisión. En este sentido, los individuos generados por los operadores genéticos deben respetar la función que describe la trayectoria temporal. Sumado a esto, la existencia de restricciones vinculadas a la finitud de los recursos implica un reto para la creación de nuevas generaciones. Así, los operadores genéticos deben garantizar en todo momento la construcción de sujetos factibles para evitar ineficiencias en la búsqueda del óptimo.

La población inicial es construida a partir de la formación de individuos que satisfagan las restricciones impuestas al caso de estudio. La distribución de colmenas es determinada aleatoriamente para el primer año, y los años siguientes son proyectados

compatibilizando lo ya obtenido mediante las operaciones genéticas. Específicamente, la estrategia para la obtención de las generaciones posteriores se puede resumir en las siguientes etapas:

PASO 1) **Selección** aleatoria de los padres y del período temporal a modificar.

PASO 2) **Cruzamiento o Mutación.** Aplicación de alguno de los operadores genéticos elegido aleatoriamente en el período seleccionado.

PASO 3) **Compatibilización**. Modificación de los períodos posteriores al cambio introducido por los operadores genéticos, respetando el desarrollo de la variable de decisión dictada por la función o heurística.

PASO 4) **Cambio poblacional**. Nuevo ordenamiento en función del fitness y eliminación de los peores individuos hasta alcanzar la cantidad de la población al inicio del procedimiento.

Se itera sobre estos pasos hasta cumplir con alguno de los siguientes criterios:

- Número máximo de iteraciones donde el mejor individuo no se altera.
- Número máximo de iteraciones.

Para seleccionar los padres (PASO 1), la población es ordenada en función de su valor de fitness. Tomando en cuenta ese orden, una mayor chance de selección es otorgada a aquellos individuos con mayor fitness. Por ejemplo, en la Figura 3 se muestra el caso donde se seleccionan al azar dos individuos de un problema de localización de colmenas en 3 campos posibles a lo largo de 3 años. Cada gen representa un campo, agrupándose 3 genes por cada año. Luego, el segundo año resulta elegido aleatoriamente para aplicar la operación de cruzamiento. A modo ilustrativo, el total de colmenas iniciales (para t=1) de cada individuo es 82, asignadas a cada campo aleatoriamente. Si tomamos un ejemplo sencillo donde la tasa de crecimiento es del 10% lineal, cada individuo tendrá 90 colmenas en el segundo año y 99 en el tercero. La evolución del número de colmenas sigue la distribución determinada en el período inicial.

En cuanto al operador de cruzamiento (PASO 2), las parejas seleccionadas deben ser distintas en al menos 2 genes para el período elegido al azar. De esta forma se garantiza que la permutación de valores no altere la cantidad total de colmenas en los hijos resultantes. Una vez que dos individuos compatibles son seleccionados, se eligen aleatoriamente dos genes cuyas cantidades sean distintas entre los padres y cuya diferencia tenga signo opuesto. Luego, el cruzamiento se realiza tomando el valor mínimo de la diferencia entre los genes a intercambiar. Esta manipulación es necesaria para garantizar que los cromosomas tengan sentido físico. En el caso de estudio, este procedimiento asegura que el número de colmenas de los individuos resultantes respete la cantidad total que debería haber para ese período. Más aún, el cruce entre genes con una misma posición asegura que nunca se supere la cantidad máxima permitida de colmenas en cada campo.

En el caso ilustrado en la Figura 4, el i-ésimo gen del padre 1 difiere en la cantidad de colmenas asignadas al i-ésimo gen del padre 2 para i =1…3. Dado que ambos individuos tienen un total de 90 colmenas a redistribuir en el segundo año y difieren en al menos 2 genes entre sí, existe al menos un gen donde las cantidades de colmenas es superior al del otro individuo para el mismo campo (+30), y existe otro gen donde la cantidad es inferior (-10). Al permutar el mínimo de la diferencia entre el par de genes

(10) se asegura que la cantidad de colmenas en los hijos resultantes continúe siendo 90. El ejemplo planteado propone permutar los genes 2 y 3 en t=2.

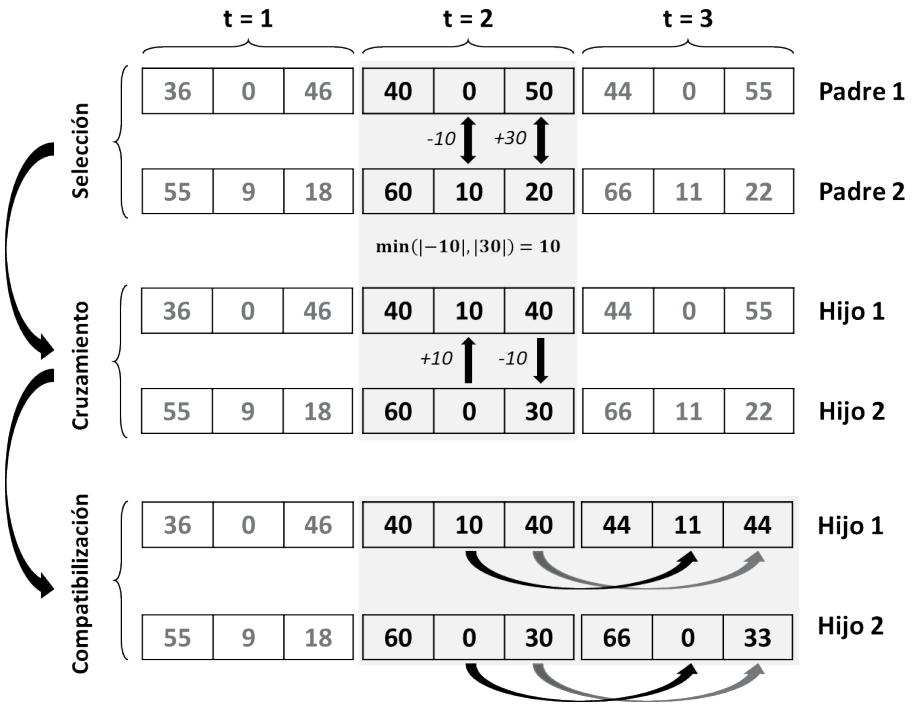

Fig. 4. Ejemplo de funcionamiento del operador de cruzamiento.

Con respecto al operador de mutación, la cantidad del gen elegido al azar de un individuo es asignada aleatoriamente a otro gen cuya cantidad es nula. Puede suceder que el gen de destino tenga una capacidad máxima inferior a la cantidad que recibirá. Si este fuese el caso, la cantidad excedente sobre el máximo se redistribuye sobre los restantes genes con valores positivos para obtener un individuo con una configuración más eficientes desde los puntos de vista económico y logístico. Cuando no existiesen genes con capacidad para recibir el remanente, este excedente se asigna al azar a otro gen con cantidad nula.

El ejemplo de la Figura 4 ilustra a ambos hijos luego de haber efectuado un cruzamiento. En particular, el segundo gen del Hijo 2 tiene valor positivo en el primer año (9), luego presenta un valor nulo en el segundo período, y finalmente vuelve a tener valor positivo en el tercero (11). Es decir, si únicamente se introdujese la modificación del operador cruzamiento, esto implicaría que las colmenas vuelven a su ubicación original en el tercer año. En términos de la representación del problema, esto podría reflejar un decisor que reversa sus decisiones constantemente. Esta aparente indecisión subyacente en la construcción de nuevos individuos es enmendada asumiendo que los cambios que introducen los operadores genéticos se mantienen hasta el final del período

bajo análisis. En el PASO 3, el tercer año se calcula nuevamente siguiendo la evolución del total de colmenas (99 unidades) en base al reordenamiento del segundo período.

5 Resultados

La complejidad del problema implementado es función del número de colmenas iniciales que el productor debe asignar a cada campo. Para la configuración de los hiperparámetros se consideró un proyecto de 500 colmenas iniciales, 30 campos potenciales en el sudoeste bonaerense (sujetos cada uno de ellos a restricciones de capacidad) y un horizonte temporal de 5 años. La selección de los hiperparámetros fue implementada utilizando un procesador Intel i7, simulando 200 casos por alternativa. La cantidad de hijos producto de la aplicación de los operadores genéticos equivale al 10% del tamaño de la población.

Se determinó que el algoritmo logra encontrar el óptimo asequible en un porcentaje superior al 68% de las veces cuando el tamaño de la población supera los 800 individuos (Figura 5). Cuando el tamaño de la población alcanza los 1200 individuos, el algoritmo encuentra dicho máximo con una probabilidad del 88%. No obstante, existe un compromiso entre precisión y velocidad de procesamiento. Mientras que una población con 800 individuos alcanzó el óptimo asequible demorando aproximadamente 86 segundos, la población con 1200 individuos encontró dicho óptimo siempre, pero duplicando el tiempo de cómputo.

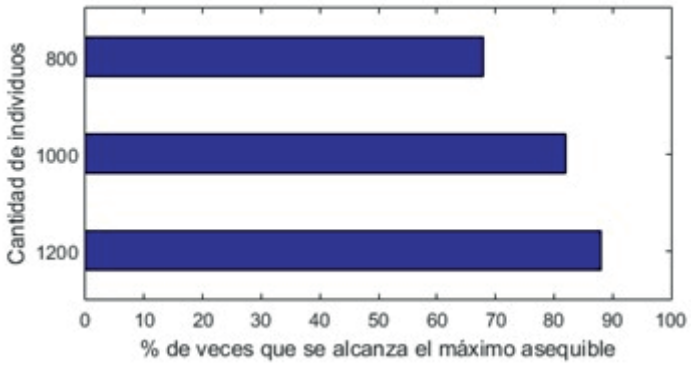

Fig. 5. Análisis del tamaño de la población.

La Figura 6 muestra que la mejor combinación se alcanza con una tasa de 10% de mutaciones para una población de 1000 individuos. Sin embargo, el máximo asequible tiene altas chances de ocurrencia a partir de una tasa del 40%.

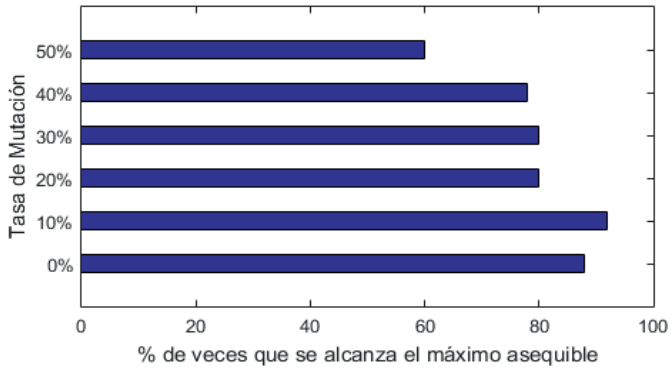

Fig. 6. Análisis del operador Mutación.

Con respecto a la velocidad del algoritmo, la implementación paralela logra reducir considerablemente los tiempos de procesamiento. Utilizando un procesador AMD FX(tm)-8120 con 8 núcleos reales, se ejecutaron 40 simulaciones por cada núcleo adicional utilizado. Tomando en cuenta la configuración óptima de los hiperparámetros, el cálculo del Speedup indica que el desempeño con 6 núcleos reduciría en hasta un 70% los tiempos de optimización en comparación con la ejecución secuencial. Más específicamente, la razón en cuestión alcanzó los 3.7 puntos.

La Figura 7 muestra la evolución del Speedup, denotándose un aumento decreciente de esta razón ante el uso de una mayor cantidad de núcleos. Cabe destacar que, si se considerase el problema base de 500 colmenas iniciales, un aumento del número de colmenas implicaría una disminución relativa de los valores de Speedup.

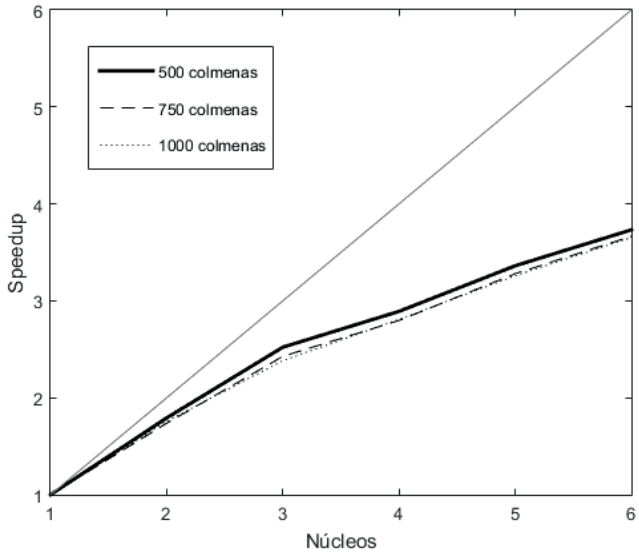

Fig. 7. Velocidad de procesamiento paralelo.

En la Figura 8 se representan los 30 campos alternativos en los cuales el productor apícola puede colocar sus colmenas. Cada uno de ellos posee una capacidad mínima de 30 colmenas y una máxima que depende del tamaño y la zona donde esté localizado el campo. Como lugar de residencia del productor se selecciona la ciudad de Bahía Blanca, representada a través del ícono violeta.

Una solución óptima factible dada por el AG consiste en colocar, en el primer año, una determinada cantidad de colmenas para la producción de miel en los campos 14, 15, 23, 28 y 30, representados a través de los íconos celestes. Es conveniente aclarar que una vez que se selecciona un campo, el mismo seguirá utilizándose hasta colmar su capacidad máxima. Conforme la aclaración anterior, para el segundo año se emplean los mismos campos que para el primer año. Luego, para el tercer, cuarto y quinto año, además de los campos del segundo año, se adicionan los campos 22 y 24, representados a través de los íconos amarillos. Los campos cuyo ícono son de color negro, corresponden a los que el AG en ninguna de sus soluciones eligió como candidatos posibles con el objeto de maximizar el VAN.



Fig. 8. Mapa con campos alternativos para el productor apícola.

Para el presente análisis, se supone que del total de colmenas que posee el productor, 150 de ellas podrán ser destinadas a dicha subactividad, en el caso que se decida llevarla a cabo. Cuando se utiliza esa cantidad de colmenas en la producción de núcleos para su posterior comercialización, la producción de miel por colmena se reduce. El AG confeccionado para este caso propone llevar a cabo esta subactividad en todos los años y considera los campos 14, 15, 23, 27, 28 ó 30 como posibles alternativas equiprobables para dicha producción. En cualquiera de ellos, el productor coloca un total de 150 colmenas que se utilizan tanto para la producción de núcleos y miel para la venta. El VAN máximo encontrado por el AG es de, aproximadamente, U$S 23.606.

6 Conclusiones

El objetivo de este estudio consiste en maximizar el valor actual neto (VAN) del eslabón primario de la cadena de valor apícola del sudoeste bonaerense, con el fin de determinar cuáles son las principales actividades que generan mayor valor a dicha producción, de modo de brindar un soporte a la toma de decisiones del productor.

Para ello, se ha diseñado e implementado un modelo de cómputo paralelo definido por un algoritmo Maestro (Master), el cual ordena las soluciones candidatas presentadas por Trabajadores (Workers) según su aptitud. Se determinó que el tamaño de la población requiere 1200 individuos para encontrar el óptimo asequible en el 88% de las simulaciones efectuadas. Respecto al operador mutación, la mejor combinación se alcanza con una tasa de 10% de mutaciones. Por último, en cuanto a la velocidad del algoritmo genético (AG), la implementación paralela logra reducir considerablemente los tiempos de procesamiento. Los resultados muestran que el VAN máximo encontrado por el AG es de, aproximadamente, U$S 23.606.

El AG aquí propuesto es una técnica de optimización para problemas dinámicos con restricciones, donde las decisiones de producción y localización pueden cambiar a lo largo del tiempo. Se busca que este modelo de cómputo pueda servir como soporte a la toma de decisiones del productor apícola con el fin de detectar oportunidades que puedan crear una ventaja competitiva. Este trabajo abre una futura línea de investigación que se centrará en estudiar, a partir de mejoras e introducción de nuevas variables y parámetros al AG propuesto en la presente investigación, el sistema de valor apícola, considerando todos sus eslabones.

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Dynamic Order Acceptance and Scheduling Approach for On-demand Production with Additive Manufacturing by Considering Idle Costs

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Abstract. Additive manufacturing (AM), particular powder bed fusion (PBF), technologies have been utilized as an advanced direct digital manufacturing approach in the on-demand production of parts for end-users. It has been predicted that, by 2030, the industry-specific AM production resources will be shared by a significant number of small and medium enterprises across all industries to achieve higher machine utilization. By then, most of the orders from customers will be processed via online 3D printing service platforms while the parts will be manufactured with distributed AM resources near to the customers. The order acceptance and scheduling (OAS) problem in on-demand production with multiple AM machines has been discussed in our previous work and the mathematic model, as well as a heuristic dynamic OAS approach, was proposed to obtain promising average profit per unit time (APT) during the whole makespan by applying properly decision-making strategies. However, the proposed mathematic model only considered the operating costs. In this paper, the mathematic model and the heuristic approach are retrofitted by considering the idle costs of AM machines to investigate the relationships between the number of AM machines and total profit can be obtained under various market demand. The experimental results indicated that, for specific market demand, the total profit obtained is not always rising as the increasing of AM machines but dropping after a certain number of AM machines.

Keywords: Order Acceptance and Scheduling, On-demand Production, Heuristic, Decision-making, Powder-bed Fusion

1 Introduction

Additive manufacturing (AM), particular powder bed fusion (PBF), technologies have been utilized as an advanced direct digital manufacturing approach in the production of

parts for end-users where can be found nowadays in various industries like aerospace and defence, biomedical, and automotive industries [1-5]. Two of the most representative PBF processes for producing of industrial level metal parts are Selective Laser Melting (SLM) and Electron Beam Melting (EBM) where thermal energy source either a laser or electron beam is used to melt and fuse selectively regions of a powder bed (ASTM:F2790-12a). Both SLM and EBM have received significant attention in the research and have been widely used in various industries for advanced applications due to their advantages of fine resolution and high quality of printing near-full density parts [2,3]. Recently, more and more manufacturers provide online 3D printing services, such as 3D Hubs, PROTOLABS, i.materialise, etc, where the customers upload their designs and place orders if they satisfy with the quote and printability feedback from the service providers. This development will put the practical order acceptance and scheduling (OAS) problems on to the table in dealing with on-demand production orders from customers around the world. Although the topic of OAS has attracted considerable attention from those who study scheduling and those who practice it over the last decades [7,8], the OAS problems in production with PBF is barely discussed.

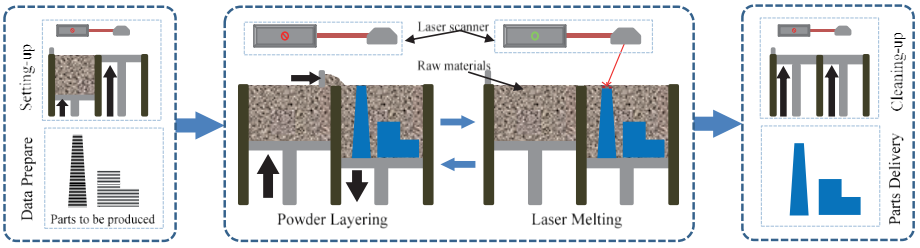

Fig. 1. Illustration of the general production process with PBF system.

The general process as shown in Fig. 1. Illustration of the general production process with PBF system. and characteristic of production with PBF systems have been introduced in our previous works [9-13], where a PBF system is treated as a kind of batch processing machine (BPM) in which a batch of identical or non-identical parts can be processed simultaneously according to the machine's capacity. Production with PBF systems is similar to a serial batch scheduling problem where the processing time of each batch is a function of jobs' attributes. The producing of a batch of parts with PBF system is usually called an AM job, and the processing time as well as the cost of the job not only depends on the total material volume of parts assigned to the job but also significantly affected by the maximum height of the parts. This makes the production planning and scheduling of AM jobs more difficult as the production time of an AM job is unascertainable before all the parts assigned to the job got confirmed. The unique characteristics of production with PBF systems have been analysed in our previous work [11], and the related works both in OAS and batch processing problems (BPP) have been reviewed as well. Although various approaches have been developed for various OAS problems and BPP problems, it is hard to adopt these approaches directly in on-demand production with PBF systems due to the unique nature of AM production [11].

Regarding the characteristics of production with PBF systems, the dynamic OAS problem in on-demand production with multiple PBF AM machines was defined and mathematically modelled with constraints of orders' arrival time and the due date for the first time in our previous work [11], and a strategy-based heuristic decision-making approach was proposed for the generation of feasible schedule solutions. The experimental results indicated that, with a given service price and due date, promising profitability can be obtained by applying properly decision-making strategies. However, the idle costs of AM machines were not considered thus the total profit obtained always increasing as the increasing of the number of AM machines. In reality, an idle cost, usually caused by site use fees and cost of capital, occurs no matter whether the machine is running. Therefore, more AM machines will defiantly obtain more revenue by processing more orders, but also cause more idle costs which might reduce the total profit.

In this paper, the mathematic model of dynamic OAS problem in on-demand production with multiple PBF AM machines is retrofitted based on our previous work by considering the idle costs of each AM machine. The rest of the paper is organized as follows. The problem addressed in this paper is defined and modelled mathematically in Section 2. In Section 3, the heuristic procedures for the generation of feasible schedule results, as well as the decision-making strategies to obtain better solutions, are proposed. An experimental study is designed and conducted with the proposed heuristic procedures and various decision-making strategies to demonstrate the relationships between obtained total profit and the number of AM machines under specific market demands in Section 4, followed by conclusions and future research direction in Section 5.

2 Problem statement

2.1 Problem definition and assumptions

This paper studies the dynamic OAS problem in an on-demand additive manufacturing environment where a set of part orders $\boldsymbol{N}$**={1,2,3,…,n}** are randomly placed by customers in chronological order, and the service provider with a set of AM machines $\boldsymbol{M}$**={1,2,3,…,m}** makes decisions on which part order should be accepted and how to schedule the accepted part orders simultaneously to maximize the average profit-per-unit-time (***APT***) obtained during the whole makespan. To further specify the problem addressed in this paper, the following assumptions are made:

- The machines considered in this paper are PBF systems with SLM/EBM processes used for metal parts production which can only handle one AM job at a time, and all the machines are available at the beginning;
- The part orders received by the service providers are from those customers satisfied with the service price and would like to place the orders if the parts can be delivered by the promised due date. Otherwise, the customers will either further negotiate with the service provider for a new offer or turn to another service provider;
- A part order is regarded as one digital model which has been properly oriented with necessary support structures according to the requirements of SLM/EBM

process, and the bottom side of the digital model needs to be put onto the building platform of the machine;

- A batch of parts assigned to a machine's job is feasible only when the parts can be placed in the machine without overlapping with each other which can be measured with the boundary box of a part order's digital model, and all the parts assigned to a machine's job will be processed simultaneously;
- A specific idle cost based on the site use fees and capital costs occurs along the time on each AM machine no matter whether it is running.

2.2 Mathematics model and constraints

The notations and decision variables used to formulate the mathematical model of the dynamic OAS problem in on-demand production with PBF AM machines are given in Table 1 and Table 2.

Table 1. Notations and decision variables.

Notations	Descriptions
i, j, k	The index used for part orders $i \in N$, AM jobs $j \in N$, and PBF machines $k \in M$
h_i, l_i, w_i, v_i, r_i	The boundary height, length, width, material volume, and the arrival time of part order i
W_k, L_k, H_k	The maximum width, length, and height of building space on machine k
ST_k, VT_k, HT_k	The time for setting up a new job, forming per unit volume of material, and coating per unit height of material respectively for machine k
HC_k	The cost of human work per unit time for machine k
TC_k	The operation cost per unit time for machine k
MC_k	The cost of per unit volume of material on machine k
IC_k	The idle cost per unit time for machine k
PV_k	The service price per unit volume of material for machine k.

Table 2. Decision variables used

Decision variables	Descriptions
$JST_{k,j}, JCT_{k,j}$	The start and completion time of the jth job on machine k
$JPP_{k,j}$	The profit obtained from the jth job on machine k
$JPC_{k,j}, JPT_{k,j}$	The production cost and time of the jth job on machine k
MS	The makespan of the schedule
APT	The average profit per unit time of the schedule
$X_{k,j,i}$	Variable to determine if part order i is accepted and assigned to thej^{th} job on machine k
$Y_{k,j}$	Variable to determine if the jth job on machine k is assigned with any parts
t	The system time $t \in [0, T]$

The objective of the dynamic OAS problem in on-demand production with multiple PBF AM machines is to maximize the total profit obtained within the makespan for the whole system which results in the maximize of the average-profit-per-unit-time (represented as ***APT***). The makespan of the whole system ***MS*** is defined as the time duration from the start of the first AM job to the completion of the last AM job. While the total net profit is calculated as total profit obtained through scheduled AM jobs minus the total idle costs of all the AM machines. Particularly, the idle cost of the AM machine k, represented as $\boldsymbol{IC_k}$, is the costs occurs no matter whether the machine is running such as the site use fees, cost of capital and management fees. While the production costs are caused due to the operation, materials and energy consumption, which occurs only when the machine in using The models of production cost, as well as the production time of an AM job are adopted from our previous work [11,13]. The objective function of the dynamic OAS problem by considering the idle costs of machines can be formulated as follows:

$$\boldsymbol{max\ APT} = \frac{\sum_{k\in M}\sum_{j\in N} \boldsymbol{JPP_{k,j}} - \sum_k (\boldsymbol{MS}\cdot \boldsymbol{IC_k})}{\boldsymbol{MS}} \tag{1}$$

Where

$$\boldsymbol{MS} = \max_{k\in M, j\in N}\{\boldsymbol{JCT_{k,j}}\} - \min_{k\in M, j\in N}\{\boldsymbol{JST_{k,j}}\} \tag{2}$$

$$\boldsymbol{JPP_{k,j}} = (\boldsymbol{PV_k} - \boldsymbol{TC_k}\cdot\boldsymbol{VT_k} - \boldsymbol{MC_k})\cdot\sum_{i\epsilon N}\boldsymbol{v_i}\cdot\boldsymbol{X_{i,k,j}} - \boldsymbol{TC_k}\cdot\boldsymbol{HT_k}\cdot\max_{i\epsilon N}\{\boldsymbol{h_i}\cdot \boldsymbol{X_{i,k,j}}\} - \boldsymbol{ST_k}\cdot\boldsymbol{HC_k}\cdot\boldsymbol{Y_{k,j}} \tag{3}$$

In the environment of on-demand production with PBF systems, several constraints are considered in scheduling part orders to PBF AM machines (detailed constraints please refer to our previous work [11]):

- Part orders can be assigned to an AM job on a PBF machine only when they can be placed on the machine's building platform without overlapping with each other, and any part order is not higher than the maximum height supported by the machine;
- A part order can only either be assigned to an exact AM job on a particular PBF machine or be rejected, and the machine can only handle one AM job at a time thus the AM jobs have to be scheduled to the machine in sequence;
- A part order is available for scheduling only after its arrival thus the start time of an AM job should be no earlier than any part order's arrival time assigned to the job, and the completion time of the job should be no later than the promised due date of any part order in the job.

3 Heuristic procedures and decision-making strategies

3.1 Heuristic procedures for dynamic OAS

The problem of dynamic OAS is a joint decision on order acceptance and BPM scheduling both of which have been proved as strong NP-hard problems. Additionally, the

generation of a feasible schedule solution, in particular batching part orders to form an AM job, is an extremely complicated procedure when considering the constraints of the machine's capacity as well as the arrival time and due date of each part order. Therefore, heuristic procedures are proposed in our previous work to generate feasible schedule solutions for solving the dynamic OAS problem efficiently. A feasible schedule solution is generated with two repetitive steps. Firstly, each AM machine will try to form a potential feasible AM job temporally through selecting available part orders from a waiting list where one part order can be selected by any AM machine simultaneously. Secondly, one of the potential feasible AM jobs will be selected and confirmed for production when either time limits or capacity limits were reached. Particularly, a Python function implemented by Jacobs [21] is used to measure whether a part could fit in a machine's building platform by considering the parts already included in the job. The Python function is capable to calculate whether a basket of rectangles (defined with the width w_i and length l_i of each part) could fit in a larger rectangle (defined with the width W_k and length L_k of the machine's building platform). Once an AM job was confirmed, all the part orders assigned to this job will be removed from the waiting list and any other potential feasible AM jobs will be reset by removing all the temporally assigned part orders. Also, a part order will be rejected if it has not been assigned to any machine until none of the machines can produce it by the promised due date. These two steps will keep repeating until no available part order waiting for scheduling. The heuristic procedures are illustrated in Fig. 2.

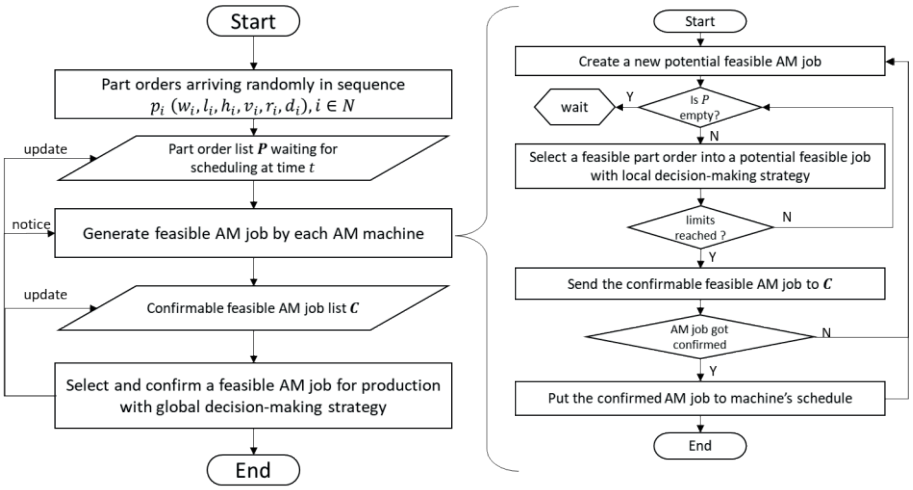

Fig. 2. Heuristic procedures for dynamic OAS in on-demand production with PBF systems.

One of the most important decisions need to be made is to confirm when is a potential feasible AM job ready for scheduling to a machine. An AM job can process a batch of non-identical parts simultaneously, and the production time of the job is a function of the properties of all parts assigned to this job as well as the specifications of the AM

machine to conduct this job. The available time slot for a feasible AM job, which is illustrated in Fig. 3, is constrained by the possible earliest start time of the job and the earliest promised due dates to the part orders assigned to the job.

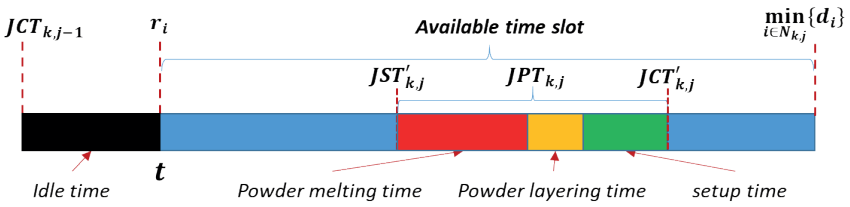

Fig. 3. An available time slot for an AM job in scheduling.

An AM job can be started when the previous job scheduled to this machine has been completed, and also the start time of the job could not be earlier than the current time t. We say an AM job is feasible so long as its start time and completion time are located within its available time slot. At the time moment t, the available time slot $TS_{k,j}$ for the jth job on machine k can be formulated as follows:

$$TS_{k,j} = [max\{t, JCT_{k,j-1}\}, \min_{i \in N_{k,j}}\{d_i\}] \tag{4}$$

A feasible AM job should be considered to be confirmed for production when the time limits are reached no matter whether the machine still has available capacity to accommodate another part order. The time limits can be measured as follows:

$$\min_{i \in N_{k,j}}\{d_i\} - \max\{t, JCT_{k,j-1}\} \leq JPT_{k,j} \tag{5}$$

where $N_{k,j}$ is the set of parts assigned to the jth job on machine k.
However, in the case of the time limits is not reached yet but no part orders can be fitted into the machine any more, which is called capacity limits, the feasible AM job also should be considered to be confirmed for production. Once an AM job has been confirmed, the start time of the job $JST_{k,j}$ should be adjusted to the earliest possible available start time that is $max\{t, JCT_{k,j-1}\}$, and accordingly the completion time of the job $JCT_{k,j}$ equals $JST_{k,j} + JPT_{k,j}$. The production time of an AM job can be calculated as follows:

$$\boldsymbol{JPT_{k,j} = VT_k \cdot \sum_{i \epsilon N} v_i \cdot X_{i,k,j} + HT_k \cdot \max_{i \epsilon N}\{h_i \cdot X_{i,k,j}\} + ST_k \cdot Y_{k,j}} \tag{6}$$

3.2 Decision-making strategies

Dynamic OAS in on-demand production with multiple PBF systems is a strong NP-hard problem where it is hard to generate all the possible schedule results within a reasonable duration particular for the problems with a big number of part orders and AM machines. Therefore, in our previous work [11], a set of decision-making strategies were proposed for the selection of available part orders to form a potential feasible AM

job as well as for the selection of potential feasible AM jobs to schedule. The performance of different decision-making strategy has been evaluated by compressing the schedule results with the best and worst results generated by randomly selection of part orders and AM jobs.

Three local decision-making strategies, named ***LPMS, LPPT, LFIFO***, and two global decision-making strategies, named ***GPMS*** and ***GPPT***, were proposed for the selection of part orders and selection of feasible AM jobs respectively. The combination of global and local decision-making strategies results in total six different strategy sets named ***GPMS-LPMS, GPMS-LPPT, GPMS-LFIFO, GPPT-LPMS, GPPT-LPPT***, and ***GPPT-LFIFO*** respectively which is described in **Table 3**. The experimental results indicated that it is practical to obtain promising APT as well as total profit for dynamic OAS in on-demand production with multiple PBF systems by applying properly decision-making strategies. The best schedule result for each test problem always can be obtained by applying one of the proposed decision-making strategy set, and particularly the APT obtained with GPMS-LPPT strategy set is 29.1% higher in average than the best results with random selection for all the 20 tested problems.

Table 3. Decision-making strategies for OAS in on-demand production with PBF systems.

Strategy set	Descriptions
GPMS-LPMS	Select part order with maximum $PMS_{k,j}^{i}$ and select feasible AM job with maximum $PMS_{k,j}$.
GPMS-LPPT	Select part order with maximum $PPT_{k,j}^{i}$ and select feasible AM job with maximum $PMS_{k,j}$.
GPMS-LFIFO	Select part order with minimum r_i and select feasible AM job with maximum $PMS_{k,j}$.
GPPT-LPMS	Select part order with maximum $PMS_{k,j}^{i}$ and select feasible AM job with maximum $PPT_{k,j}$.
GPPT-LPPT	Select part order with maximum $PPT_{k,j}^{i}$ and select feasible AM job with maximum $PPT_{k,j}$.
GPPT-LFIFO	Select part order with minimum r_i and select feasible AM job with maximum $PPT_{k,j}$.

To select a new part order i into a potential feasible AM job j on machine k, the average profit per unit time to be obtained by this job during the whole makespan represented as $PMS_{k,j}^{i}$ and the ratio of the production time of this job to the whole makespan represented as $PPT_{k,j}^{i}$ are considered as decision variables. Also, the arrival time of the part order r_i is considered as decision variable which may reduce the idle time of the machine. The $PMS_{k,j}^{i}$ and $PPT_{k,j}^{i}$ can be formulated as follows:

$$\boldsymbol{PMS_{k,j}^{i}} = \frac{\boldsymbol{JPP_{k,j}^{i}}}{\boldsymbol{JST_{k,j}^{i}+JPT_{k,j}^{i}}} \tag{7}$$

$$\boldsymbol{PPT_{k,j}^{i}} = \frac{\boldsymbol{JPT_{k,j}^{i}}}{\boldsymbol{JST_{k,j}^{i}+JPT_{k,j}^{i}}} \tag{8}$$

Where $\boldsymbol{JPT}_{\boldsymbol{k,j}}^{\boldsymbol{i}}$, $\boldsymbol{JPP}_{\boldsymbol{k,j}}^{\boldsymbol{i}}$, and $\boldsymbol{JST}_{\boldsymbol{k,j}}^{\boldsymbol{i}}$ represents the production time, profit and start time of the job j if part order i was assigned to this job. Accordingly, if the job j was scheduled to machine k, the profit per unit time to be obtained during the whole makespan represented as $PMS_{k,j}$ and the ratio of total production time to the whole makespan represented as $PPT_{k,j}$ are considered as decision variables to select a potential feasible AM job for scheduling. The $PMS_{k,j}$ and $PPT_{k,j}$ can be formulated as follows:

$$\boldsymbol{PMS}_{\boldsymbol{k,j}} = \frac{\sum_{\boldsymbol{k\in M, j\in N}} \boldsymbol{Y}_{\boldsymbol{k,j}} \cdot \boldsymbol{JPP}_{\boldsymbol{k,j-1}} + \boldsymbol{JPP}'_{\boldsymbol{k,j}}}{\boldsymbol{MS_j}} \tag{9}$$

$$\boldsymbol{PPT}_{\boldsymbol{k,j}} = \frac{\sum_{\boldsymbol{k\in M, j\in N}} \boldsymbol{Y}_{\boldsymbol{k,j}} \cdot \boldsymbol{JPT}_{\boldsymbol{k,j-1}} + \boldsymbol{JPT}'_{\boldsymbol{k,j}}}{\boldsymbol{MS_j}} \tag{10}$$

4 Computational study

4.1 Experiment design

The computational study is conducted to investigate the relationships between the number of AM machines and the APT as well as the total profit can be obtained under various market demand when considering the idle cost of each AM machine. A series of test problems are designed to demonstrate various on-demand AM production environments. Each test problem consists of different numbers of AM machines with the same specification and different numbers of part orders which arrived randomly during a specific time duration.

The specifications of the AM machines are given empirically as shown in Table 4, while the parameters of part orders are generated randomly with specific arrival time r_i, boundary dimensions ($h_i \times w_i \times l_i$), material volume v_i, and the due date d_i promised by the service provider. All the parts are assumed to arrive randomly within 30 days. The random ranges of parameters for the part orders used in this paper are shown in Table 5.

Table 4. Specifications of AM machines used for the experiment.

Parameters	Values
$H_k \times W_k \times L_k$, (cm^3)	32.5×25×25
VT_k, $(hour/cm^3)$	0.030864
HT_k, $(hour/cm)$	0.7
ST_k, $(hour)$	2
TC_k, (GBP/cm^3)	60
HC_k, $(GBP/hour)$	30
MC, (GBP/cm^3)	2
P_k, (GBP/cm^3)	6
IC_k, $(GBP/hour)$	0, 1.5, 5

Table 5. Parameters of part orders used for the experiment.

Parameters	Random Range	Example
r_i, (time moment in hours)	0~720	439
d_i, (time moment in hours)	$r_i + 336$	775
h_i, (cm)	2~32	20
w_i, (cm)	2~25	9
l_i, (cm)	2~25	10
v_i, (cm^3)	$h_i \times w_i \times l_i \times$ (0.3~0.8)	1132

Seven levels of the number of AM machines (1, 3, 5, 7, 10, 15, and 20) are considered for each size of test problem according to a different number of part orders (50, 150, and 300) to demonstrate various market demand. Particular, three levels of idle cost ($IC_k = 0, IC_k = 1.5\ and\ IC_k = 5.0$) are considered for each problem to investigate the influence of idle cost on the performance of a different number of AM machines. The proposed heuristic procedure was implemented in Python language, and all experiments were performed on a computer equipped with Intel® Core™ i7-7700 CPU @3.60GHz processors and 32 GB RAM.

4.2 Experiment results

According to the discovery in our previous work, the performance of each decision-making strategy set is affected by the changing of market demand where the best schedule result was generated by applying one of six decision-making strategy set but by one specific strategy set. Therefore, each test problem was solved by applying all the six decision-making strategies and the best schedule result of each problem is used for the investigation of the relationships between the number of machines and the market demand. Also, as the total profit equals APT multiply by the whole makespan, they are equivalent when used for analyzing the performance of the machines. The total profit generated by various number of AM machines ($IC_k = 5.0$) with different decision-making strategy sets under market demand of 150 part orders is shown in Table 6 for example. It can be seen that the best results were presented by different decision-making strategy set, and the maximum total profit increasing as the number of AM machines increasing from 1 to 15. However, the total profit is reduced from £349,288 to £326,480 when the number of AM machines increased from 15 to 20.

Table 6. The total profit generated by machines with different decision-making strategy.

	Total Profit (£)						
M	GPMS_ LPMS	GPMS_ LPPT	GPMS_ LFIFO	GPPT_ LPMS	GPPT_ LPPT	GPPT_ LFIFO	BEST RESULT
1	**50024**	49817	28616	50024	49817	28616	**50024**
3	**143223**	135149	114523	142608	135149	114523	**143223**
5	200793	198037	204107	200793	198037	**204895**	**204895**
7	205712	222114	**280841**	205712	228447	278032	**280841**

10	191303	219219	321565	191303	225552	**330428**	**330428**
15	167288	195924	347951	167288	202256	**349288**	**349288**
20	143274	172628	326414	143274	178961	**326480**	**326480**

To further investigate the changing of total profit with various number of AM machines, the maximum total profit generated by various number of AM machines with different decision-making strategy sets under market demands of 50, 150, and 300 part orders are compared and illustrated in Fig. 4.

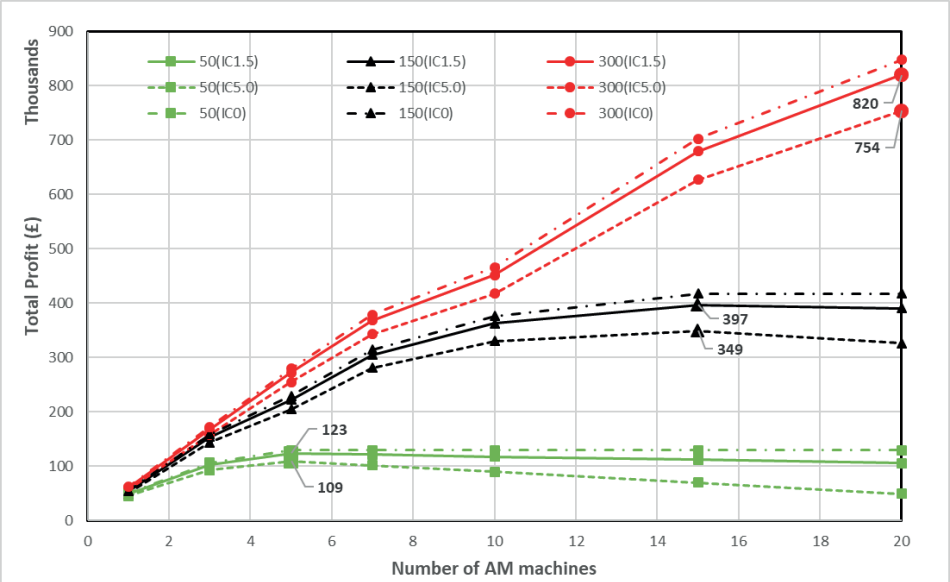

Fig. 4. Relationships between the numbers of AM machines and obtained total profit.

It can be seen that the total profit always lower when the value of IC_k higher for any size of market demand and the difference become bigger along with the growth of the number of AM machines. Under the market demand of 300 part orders, the total profit keep increasing along with the growth of the number of AM machines while the increasing speed is dropping slightly. However, for the market demand of 50 and 150 part orders, the maximum total profit is obtained at 5 and 17 AM machines respectively and then dropping along with the growth of the number of AM machines. It is interesting to note that, when the idle cost was not considered ($IC_k = 0$), the total profit remains unchanged when it reached a specific level for market demand of 50 and 150 part orders.

Based on the analyses of the experiment results, we can say that a proper number of AM machines should be invested to match with a specific level of market demand particular for service providers who need to pay a high site use and administrative fees. The approach proposed in this paper can be used for the decision making on the number of AM machines to be invested through simulation with predicated market demand.

However, the service price as well as the promised due date is assumed to be fixed for the experiment conducted in this research, which means the competitiveness of the service provider is restricted. While in an online 3D printing service platform where exist multiple service providers, a service provider can improve their competitiveness by offering a lower price and/or shorter due date to attract more part orders.

5 Conclusions and future research

This study introduced the dynamic OAS problem in on-demand production with multiple PBF systems by considering the idle cost of each machine. The mathematic model, as well as the heuristic procedure, was retrofitted based on our previous work for the investigation of the relationships between the number of machines and the total profit can be obtained under various market demand levels. A computational experiment was designed and conducted which consists of a series of test problems by considering different market demand levels, number of AM machines, and idle cost for each AM machine. The experiment results indicated that the total profit is increasing along with the growth of the number of AM machines when the market demand is big enough. However, when the market demand relative smaller, the maximum total profit obtained at a specific number of AM machines and then dropping along with the growth of the number of AM machines. The proposed decision-making strategy-based heuristic approach has been demonstrated in our previous work [11] that it is practical to solve the dynamic OAS problem in on-demand production with PBF systems, and also it can be used as an analytic tool to find out proper promised due date to maximize profit. By considering idle cost in this paper, the proposed heuristic approach can be further considered as a tool for the decision making on the number of AM machines to be invested through simulation with the predicated market demand.

As an emerging disruptive manufacturing technology, the applications of PBF technologies has been increased substantially in various industries during the past years, and considerable research has been carried out from scientific and technological challenges to business models innovations as well as industrial application issues[5,6,15-20]. However, the study on production planning particular OAS problems in on-demand production with PBF systems is just catching up. Most recently, the dynamic OAS problems in on-demand production with PBF systems have been discussed in our reported works and a decision-making strategy based heuristic approach was proposed for the environment with individual service provider[11] as well as with multiple competitive service providers[12,14]. The proposed heuristic approach has been validated through comprehensive experimental study where promising schedule results can be obtained by applying properly decision-making strategies. However, further investigations need to be carried out for practical applications. Firstly, the proposed mathematic model, as well as the cost structures, can be further extended by considering true shape 2D/3D nesting algorithms to cover more industrial AM processes such as Selective Laser Sintering (SLS) and binder jetting (ASTM:F2790-12a). Secondly, advanced methodologies based on machine learning and/or bio-inspired algorithms are expected for the development of optimal decision-making strategies. Furthermore, the competitive

mechanism among service providers need to be investigated and a high-efficiency heuristic approach needs to be developed to support the generation of competitive offers with flexible price and due date.

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A Decomposition Approach for the Combined Inventory Routing and Scheduling Problem

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Abstract. The combined Inventory Routing Problem and Crew Scheduling problems are studied in this work based on a mathematical formulation for the combined problems. Given the complexity of the mathematical models proposed a decomposition approach composed by three different phases is proposed: Inventory – Routing and Crew allocation, therefore the global problem is solved iteratively by solving first the Inventory sub-problem, these results are used as an input for the Routing sub-problem and it is solved, then these solutions are used as an input for the Crew allocation sub-problem and then solved. We have used an optimization software that allow us to solve iteratively these sub-problems and get the optimal solution for each phase of the decomposition. The general assumptions of the decomposition are presented along with some preliminary results of our proposal. To get the results we have adapted the well-known instances of the classic Inventory Routing Problem adding new elements such us drivers, schedules, hours per day, among others.

Keywords: Inventory Routing Problem, Crew Scheduling Problem, Decomposition Approach.

1 Introduction

Decisions of inventory and routing are interrelated in distribution networks and in supply chains, for example in [1] an application the combination of transportation and inventory management in a gas company is presented. In this sense, several computational and real life applications have been developed for study these combined problems [2]–[6]. An exact approach for this problem is developed in [7] where authors proposed an exact model using the branch and cut strategy including the evaluation of two inventory strategies. On the other hand, shift and crew scheduling also affects the distribution planning process. The work presented in [8] one of the first works that combine these three different elements into one model.

In this research we propose an extension of the classical Inventory Routing Problem by including the crew scheduling problem considering breaks in the planning process and propose a decomposition strategy.

2 Problem Description

The problem is formulated by joining two different well known problems, the first one the classic Inventory Routing Problem which is defined over a graph G=(V,A) where $V = \{v_1, \dots, v_{n+1}\}$ corresponds to the set of nodes where the first node represents the central depot or warehouse and the rest of the nodes corresponds to the customers. On the other hand the set of arcs $A = \{(i,j) \mid i,j \in V, i \neq j\}$ that creates the distribution routes between the customers and the depot. The supplier from a central depot must satisfy the demand of a subset of customers $V_p = V \setminus \{1\}$, the demand is assumed to be deterministic and varies for each period time where in each period time it can be chosen the shift where the product can be delivered. Also, there is a set of drivers that must be assigned to vehicles and shifts to distribute the product over the customers.

3 Solution Approach and Some Results

The proposed method consists in solving exactly the sub-problems proposed joining the results obtained with the next phase of the decomposition. In this sense, the proposed decomposition is presented in Algorithm 1.

Algorithm 1. Decomposition proposed.

Decomposition Approach	
1:	Define planning horizon $\lvert\mathcal{T}'\rvert$
2:	for t in $\mathcal{T}'$, do
3:	Solve inventory_model()→ s_1
4:	$Isolit \leftarrow Iit - SOit \ \forall i \in \mathcal{V}; t \in \mathcal{T}'$
5:	$qsolikft \leftarrow qikft \ \forall i \in \mathcal{V}; k \in \mathcal{K}; f \in \mathcal{F}; t \in \mathcal{T}'$
6:	$ysolikft \leftarrow yikft \ \forall i \in \mathcal{V}; k \in \mathcal{K}; f \in \mathcal{F}; t \in \mathcal{T}'$
7:	If s_1 is optimal or feasible then
8:	Solve routing_model()→ s_2
9:	$xsolijkft \leftarrow xijkft \ \forall i \in \mathcal{V}; j \in \mathcal{V}; k \in \mathcal{K}; f \in \mathcal{F}; t \in \mathcal{T}'$
10:	$esolikft \leftarrow eikft \ \forall i \in \mathcal{V}; k \in \mathcal{K}; f \in \mathcal{F}; t \in \mathcal{T}'$
11:	$wsolkft \leftarrow wkft \ \forall k \in \mathcal{K}; f \in \mathcal{F}; t \in \mathcal{T}'$
12:	Else: Break
13:	If s_2 is optimal or feasible then
14:	Solve personnel_model()→ s_3
15:	$gsoldhorizonte \leftarrow gdhorizonte \ \forall d \in \mathcal{D}; t \in \mathcal{T}'$
16:	$Bi \leftarrow Isolit - \bar{X}i + dit$
17:	Else: Break
18:	End for

The Algorithm 1 is composed by the solution of three different sub-problems: The *inventory_model(),* The *routing_model()* and The *personnel_model()*. The *inventory_model()* takes as an input the planning horizon and solves a mixed integer model that minimize the total inventory costs considering constraints related to inventory levels at depot and the customers, the bounds of the inventory levels only for the customers and it considers the capacities of vehicles. In the *routing_model()* a vehicle routing problem with time windows (VRPTW) is solved aiming to minimize the traveling costs including the time windows penalizations, the constraints are related to the flow balance constraints, capacities, time windows and sub-tour eliminations and the definition of the shifts (beginning-end and break). Finally, the *personnel_model()* solves a mixed integer model to allocate drivers to shifts aiming to minimize the personnel allocation costs with constraints related to allocation of drivers in vehicles and logical constraints of vehicles with shifts and drivers.

In order to test the proposed approach, the instances proposed in [2], [7] have been adapted considering the different elements added such as drivers, time windows and shifts with breaks. The results are presented in two separate tables, Table 1 with the results of 5 customers and Table 2 with the results of 10 customers. The metrics used to analyze the results are the routing costs, the average of vehicles used per period time, the average occupation of vehicles, the crew costs, the average cost per driver and the average occupation of drivers. The model were solved using Xpress-MP.

Table 2. Results with 5 customers.

Resources	5 customers					
	Routing cost	Avg of Vehicles per period	Avg Occupation of vehicles	Personnel cost	Avg Cost per driver	Avg Occupation of drivers
2 Vehicles						
2 Drivers	23591,384	1,816	79,432	14,478	0,134	4,938
3 Drivers	23591,384	1,816	79,432	104,274	1,168	33,434
4 Drivers	23591,384	1,816	79,432	256,836	3,3	81,014
5 Drivers	23591,384	1,816	79,432	279,904	3,634	90,772
6 Drivers	23591,384	1,816	79,432	288,236	3,834	90,228
3 Vehicles						
2 Drivers	65815,46	2,032	56,598	15,642	0,2	4,552
3 Drivers	65815,46	2,032	56,598	82,334	1,202	30,12
4 Drivers	65815,46	2,032	56,598	193,502	2,534	60,704
5 Drivers	65815,46	2,032	56,598	266,43	3,966	81,022
6 Drivers	65815,46	2,032	56,598	279,988	4,164	82,79
5 Vehicles						
4 Drivers	120944,9	2,084	34,908	91,472	1,4	34,1
5 Drivers	120944,9	2,084	34,908	204,75	3,966	68,592
6 Drivers	120944,9	2,084	34,908	245,666	4,866	80,898
10 Drivers	120944,9	2,084	34,908	252,52	5,402	83,43
10 Vehicles						
5 Drivers	110680,656	0,882	7,16	24,884	0,234	4,968
10 Drivers	110680,656	0,882	7,16	114,418	3,634	47,948
20 Drivers	110680,656	0,882	7,16	111,402	4,768	40,662

Table 2. Results with 10 customers.

Resources	10 customers					
	Routing cost	Avg of Vehicles per period	Avg Occupation of vehicles	Personnel cost	Avg Cost per driver	Avg Occupation of drivers
2 Vehicles						
2 Drivers	93220,86	2	88,818	0	0	0
3 Drivers	92957,26	2	89,694	33	0,332	8,224
4 Drivers	92957,26	2	89,694	281,25	3,33	79,606
5 Drivers	92957,26	2	89,694	282,542	3,866	84,984
6 Drivers	93220,86	2	89,622	314,142	4,298	91,146
3 Vehicles						
2 Drivers	188193,44	2,248	62,972	0	0	0
3 Drivers	188193,24	2,248	63,342	4,012	0,1	1,322
4 Drivers	188193,24	2,248	63,342	90,168	1,634	37,648
5 Drivers	183172,44	2,182	61,852	183,232	3,432	67,54
6 Drivers	284012,12	1,734	47,274	197,84	4,634	78,55
5 Vehicles						
4 Drivers	240668,2	1,948	31,576	15,608	0,266	4,404
5 Drivers	240668,2	1,948	31,576	67,886	1,632	27,098
6 Drivers	240764,2	1,948	31,8	121,176	3,432	53,622
10 Drivers	255243,4	1,964	31,614	184,732	5,866	82,502
10 Vehicles						
5 Drivers	87717,5	0,65	4,98	0	0	0
10 Drivers	87717,5	0,65	4,98	29,084	1,6	13,134
20 Drivers	87717,5	0,65	4,98	26,36	2	10,99

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Resolución de los problemas Order Batching / Picking a través de un Algoritmo Evolutivo

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Abstract. En este trabajo se propone un algoritmo evolutivo para resolver de manera combinada el Order Batching Problem y el Order Picking Problem. Este problema combinado consiste en seleccionar y recoger en lotes varios artículos de pedidos de distintos clientes de forma simultánea desde un área de almacenamiento y dado un plazo para la finalización del armado de cada pedido conforme a un plan de distribución. Se busca determinar el plan que minimiza el costo total del proceso de picking, el que será directamente proporcional al tiempo de desplazamiento en el área de almacenamiento, al tiempo para recoger cada artículo y descargarlo en el área de despacho y a la puntualidad en el armado de cada pedido, en el sentido de que la anticipación o la demora acarreará costos por ineficiencia en el uso del espacio o por incumplimientos del plan de distribución. Del análisis de los resultados alcanzados, al compararlos con otros resultados extraídos de la literatura, se observa un buen desempeño del algoritmo propuesto en este trabajo.

Keywords: Order Batching, Order Picking, Algoritmo Evolutivo.

1 Introducción

La optimización de procesos dentro de un centro de distribución es un factor crítico para el desempeño operativo de la logística interna y externa de la empresa. Estos procesos operativos están relacionados a los movimientos de mercaderías dentro de los centros de distribución, como el de recepción, ubicación, almacenamiento, selección y

recolección de pedidos, clasificación y despacho [1] [2]. El almacenamiento, hace referencia a la guarda física de los artículos a la espera de un pedido. La selección y recolección de estos artículos es el proceso principal en la mayoría de los depósitos. Consiste en tomar desde las ubicaciones de almacenamiento correspondientes, la cantidad correcta de los artículos correctos en base a lo requerido por los clientes en sus pedidos, para transportarlos hacia la zona de preparación de los pedidos [3]. La clasificación de los pedidos seleccionados y recolectados consiste en la reagrupación de las unidades de cada lote en los pedidos individuales de cada cliente una vez que se completa el proceso de picking [4] [5]. En la mayoría de los casos este proceso incluye las actividades de marcado y etiquetado, de embalaje y agrupamiento en una unidad indivisible de carga. El despacho es el proceso que involucra la verificación de cada unidad de carga chequeando que los pedidos estén completos, la elaboración de los documentos necesarios para poder despachar la mercadería y finalmente la carga de la misma al medio de transporte. El presente trabajo se enfoca en la optimización del proceso de selección y recolección de pedidos.

2 Descripción del problema y revisión de la literatura

Respecto a los mencionados procesos operativos relacionados al movimiento de mercaderías dentro de los depósitos, se identifican claramente tres problemas. El primero de ellos, es la asignación de los artículos ingresados a diferentes posiciones de almacenamiento. El segundo, es el agrupamiento de artículos de pedidos de clientes en lotes para su recolección. Y el tercero, es la programación de la secuencia de recolección de los artículos realizada por los equipos de picking y el traslado al área de despacho [6] [7] [8]. En este trabajo nos enfocamos en el tratamiento integrado de estos dos últimos problemas, dado que son críticos para la eficiencia de las operaciones del depósito e involucran la mayor parte de los costos de las operaciones del depósito, al comprender actividades intensivas en mano de obra [9] [10]. Para entender este problema primero debemos describir con mayor detalle el proceso de selección y recolección de los artículos. Este proceso comienza con el ingreso de una orden de preparación de una determinada cantidad de pedidos realizados por distintos clientes, en la que se detalla para cada pedido las cantidades y especificaciones de distintos artículos disponibles en el área de almacenamiento, y en la que se define la fecha o momento en el que debe estar disponible cada pedido en el área de despacho. Este momento está definido en base al programa de distribución y el tiempo requerido en el proceso de clasificación y despacho. Los artículos deben ser recogidos de las posiciones de almacenamiento en el menor tiempo posible, para lo que cada equipo de picking, debe visitar una secuencia de posiciones de almacenamiento con el fin de tomar los artículos solicitados. Al finalizar esta operación, se obtiene el tiempo de procesamiento de la orden y de cada uno de los pedidos. El problema integrado consiste en determinar el plan que minimiza el costo operativo del proceso de picking, esto es, el costo de seleccionar y recoger en lotes varios artículos de pedidos de distintos clientes de forma simultánea desde un área de almacenamiento determinada dado un plazo para la finalización del armado de cada

pedido, donde cada pedido está conformado por distintas cantidades de diferentes artículos y cada lote está conformado por una variedad de artículos de diferentes pedidos [11] [12] [13]. Por un lado, si se excediera el momento en que finaliza el armado del pedido respecto al momento en que dicho pedido debía estar listo, se incurriría en costos por incumplimientos del programa de distribución. Y, por otro lado, si dicho momento se anticipara se incurriría en un costo por la utilización ineficiente del área de despacho, al ocuparse con pedidos que todavía no deben ser despachados obstaculizando los flujos dentro del área aumentando sus tiempos de procesamiento [11]. Formalmente, el problema integrado está compuesto por el Order Batching Problem (OBP) y el Order Picking Problem (OPP) [14] [15] [16]. El OBP consiste en encontrar la cantidad y el tamaño óptimo de los lotes de artículos, para que cada lote sea recogido por un equipo de picking [13]. Para esto se debe considerar la capacidad del equipo de picking y el momento requerido en que debe estar cada artículo en el área de despacho para la finalización del armado de cada pedido [17] [18] [19]. El OPP consiste en identificar secuencias óptimas de visitas de las posiciones de almacenamiento en las que se encuentran cada uno de los artículos incluidos en un lote determinado [20] [21] [22]. En adelante se identifica este problema integrado como OBP+OPP. En [2] se realiza una revisión de la literatura sobre el OBP y el OPP. En [1] [21] [23] se presenta una revisión de heurísticas para el OPP. En [8] se presentan dos formas de resolución al OPP, mediante Ant Colony Optimization y mediante Iterated Local Search. En [15] se presentan otras meta-heurísticas aplicadas a los problemas de ruteo subyacentes. En [4], se utiliza un enfoque basado en el clustering para resolver el OBP teniendo en cuenta patrones de demanda en lugar de la distancia recorrida en cada secuencia de visitas. En [7] se propusieron varias heurísticas para el OBP. Luego, en [13] se propuso un modelo de programación entera para el OBP donde las distancias de cada secuencia de visita son estimadas y el problema se resuelve con una heurística basada en lógica difusa. En [11] se utiliza un algoritmo genético múltiple para resolver el OBP+OPP. Este trabajo es novedoso por la utilización de ventanas temporales flexibles para el tiempo de entrega de cada pedido. En el presente trabajo se sigue la metodología utilizada en esta última publicación, pero utilizando para la resolución del problema un algoritmo evolutivo con un cromosoma específico que facilita la utilización de diferentes números de lotes. Mediante este algoritmo se busca obtener mejoras en el desempeño comparando los resultados obtenidos sobre las instancias y configuración del lay-out propuestos en la publicación mencionada.

3 Definición de parámetros y variables

$\mathcal{P} = \{1, \dots, nArt\}$ es el conjunto de artículos, hay $nArt$ tipos de artículos diferentes y cada uno de estos tipos de artículos tiene un peso unitario determinado. El conjunto de pesos unitarios de los $nArt$ tipos de artículos se representa mediante $\mathcal{W} = \{w_1, \dots, w_p, \dots, w_{nArt}\}$. $\mathcal{P}_i$ es el subconjunto de artículos pedidos por el cliente i, es decir $\mathcal{P}_i \supset \mathcal{P}$. Además se supone que cada cliente realiza un solo pedido de varios artículos diferentes con distintas cantidades de cada uno de ellos, por lo que la cantidad de clientes, nC, es igual a la cantidad de pedidos, $nPed$, quedando el conjunto de

clientes determinado por $\mathcal{I} = \{1, \dots, i, \dots, nC\}$. Cada pedido tiene un plazo determinado para finalizar con su armado, los plazos de finalización de todos los pedidos están representados en el conjunto $\mathcal{T} = \{t_1, \dots, t_{\mathrm{i}}, \dots, t_{nPed}\}$. $\mathcal{P}_{\mathrm{r}}$ es el subconjunto de artículos diferentes presentes en el lote r. Es decir $\mathcal{P}_{\mathrm{r}} \supset \mathcal{P}$. Los artículos en $\mathcal{P}_{\mathrm{r}}$ pueden provenir de pedidos de diferentes clientes o no. $\mathcal{L} = \{\ell_0, \ell_1, \dots, \ell_{\mathrm{p}}, \dots, \ell_{\mathrm{nArt}}\}$ son las posiciones de almacenamiento de cada uno de los tipos de artículos, más ℓ_0 que es la localización del área de despacho dentro del almacén. Por ejemplo, para el artículo $p \in \mathcal{P}$, la posición de almacenamiento ℓ_{p} está dada por sus coordenadas dentro del depósito, es decir, $\ell_{\mathrm{p}} = (x_p, y_p)$. $\mathcal{R} = \{1, .., \mathrm{r}, \dots, |\mathcal{R}|\}$ es el conjunto de lotes a recoger por los operadores de los equipos de picking. Donde $|\mathcal{R}|$ es la cantidad de lotes a recoger. $\mathcal{S}_{\mathrm{r}} = \langle \mathrm{s}_1, \dots, \mathrm{s}_{\mathrm{u}}, \dots, \mathrm{s}_{|\mathcal{S}_{\mathrm{r}}|} \rangle$ es la ruta o sucesión de posiciones de almacenamiento a visitar en el lote r. Es decir, $r \in \mathcal{R}$ y $\mathcal{S}_{\mathrm{r}} \supset \mathcal{L}$. Y donde, s_u es la u-ésima posición de almacenamiento a visitar en el lote r y $|\mathcal{S}_{\mathrm{r}}|$ es la cantidad de artículos diferentes del lote r. $\mathcal{Q}$ es el conjunto de las cantidades de cada artículos pedidos por todos los clientes, donde, $q_{i,p} \in \mathcal{Q}$ es la cantidad total pedida por el cliente i del artículo p. Luego $\mathcal{Q}_i = \sum_{p \in \mathcal{P}_i} q_{i,p}$ es la cantidad total de artículos solicitada por el cliente i. $\mathcal{Q}_p = \sum_{i \in \mathcal{I}} q_{i,p}$ es la cantidad pedida por todos los clientes del artículo p. Y $\mathcal{Q}_{\mathrm{r}} \supset \mathcal{Q}$ es el conjunto de cantidades de distintos artículos agrupados en el lote r. $\mathcal{Q}_r = \{q_1, \dots, q_p, \dots, q_{|\mathcal{S}_r|}\}$. $\mathcal{K} = \{1, \dots, |\mathcal{K}|\}$ es el conjunto de equipos de picking con capacidad Cap. Luego, el problema integrado OBP+OPP, se define en un grafo no dirigido $\mathcal{G} = (\mathcal{V}, \mathcal{A})$, donde: $\mathcal{V}$ es el conjunto de nodos que representan todas las posiciones de almacenamiento (lugares físicos) de cada uno de los artículos $p \in \mathcal{P}$, más dos copias (0 y $n+1$) del nodo inicial (ubicación del área de despacho). $\mathcal{A}$ representa el conjunto de todos los arcos factibles entre todos los nodos del conjunto $\mathcal{V}$. Cada $\mathrm{arco}(h, l) \in \mathcal{A}$ tiene asociado un tiempo t_{hl} dado por la distancia entre los nodos h y l dividida por la velocidad del equipo de picking v (esto es $t_{hl} = D_{h,l}/v$) y un costo operativo por unidad de tiempo ς. Luego, t_{pick} es el tiempo medio para recoger un artículo, una vez que el operador ha llegado al punto de almacenamiento de un artículo determinado. $\mathcal{Q}_{\mathrm{i}}$ representa la cantidad total de artículos pedidos por el cliente i, donde $\mathcal{Q}_i = \sum_{p \in \mathcal{P}} q_{i,p}$. Esto significa que la cantidad total de artículos pedidos por el cliente i, q_i, está formada por la suma de las cantidades solicitadas, en ese pedido, de cada uno de los h artículos solicitados por el cliente i. $x_{hlkr} = 1$ si y solo si el artículo h es recogido inmediatamente antes del artículo l por el equipo de picking k en la secuencia del lote r, donde $h, l \in \mathcal{V}$, $k \in \mathcal{K}$ y $r \in \mathcal{R}$. Es decir, es igual a 1 si el vehículo k al recoger el lote r atraviesa el $\mathrm{arco}(h, l)$. $y_{hkr} = 1$ si y solo si el equipo de picking k recoge el artículo h en el lote r, donde $h \in \mathcal{V}$, $k \in \mathcal{K}$ y $r \in \mathcal{R}$. El modelo para el OBP+OPP es el siguiente [3] [11]:

$$\min C_{Total}: \left[\frac{\sum_{h \in \mathcal{V}} \sum_{l \in \mathcal{V}} D_{h,l} \cdot \sum_{k \in \mathcal{K}} \sum_{r \in \mathcal{R}} x_{hlkr}}{v} + \sum_{\substack{p \in \mathcal{P} \\ q \in \mathcal{Q}}} q_p \cdot t_{pick} \right] \cdot \varsigma + \sum_{i \in \mathcal{I}} (\alpha \cdot E_i + \beta \cdot T_i) \quad (1)$$

s.a.:

$$\sum_{p\in\mathcal{P}_r}(q_p \cdot w_p) \cdot y_{pkr} \leq Cap,\ \forall k \in \mathcal{K}, r \in \mathcal{R} \quad (2)$$

$$\sum_{r\in\mathcal{R}} y_{hkr} = 1,\ \forall h \in \mathcal{P}, \forall k \in \mathcal{K} \quad (3)$$

$$\sum_{k\in\mathcal{K}} y_{hkr} = |\mathcal{K}|,\ \forall h \in \{0, n+1\}, r \in \mathcal{R} \quad (4)$$

$$\sum_{h\in\mathcal{V}} x_{hlkr} = y_{lkr},\ \forall l \in \mathcal{V} \setminus \{0\}, k \in \mathcal{K}, r \in \mathcal{R} \quad (5)$$

$$\sum_{l\in\mathcal{V}} x_{hlkr} = y_{hkr},\ \forall h \in \mathcal{V} \setminus \{n+1\}, k \in \mathcal{K}, r \in \mathcal{R} \quad (6)$$

$$\sum_{i\in\mathcal{I}} \sum_{k\in\mathcal{K}} \sum_{r\in\mathcal{R}} q_{i,p} \cdot y_{pkr} = Q_p,\ \forall p \in \mathcal{P} \quad (7)$$

$$\sum_{p\in\mathcal{P}} \sum_{k\in\mathcal{K}} \sum_{r\in\mathcal{R}} q_{i,p} \cdot y_{pkr} = Q_i,\ \forall i \in \mathcal{I} \quad (8)$$

$$x_{hlkr} \in \{0,1\},\ \forall h, l \in \mathcal{V}, k \in \mathcal{K}, r \in \mathcal{R} \quad (9)$$

$$y_{hkr} \in \{0,1\},\ \forall h \in \mathcal{V}, k \in \mathcal{K}, r \in \mathcal{R} \quad (10)$$

La función objetivo (1) representa el costo total expresado en unidades monetarias por unidad de tiempo consumida en la recolección de pedidos en lotes, más una penalización por incumplimiento del plazo para finalizar el armado del pedido. El primer término de esta función, considera el tiempo de desplazamiento desde el área de preparación hasta y entre las posiciones de almacenamiento, más el tiempo de recolección, que es el tiempo requerido para recoger cada artículo una vez que se ha llegado a la posición de almacenamiento. El tiempo de desplazamiento surge del cociente entre la distancia recorrida y la velocidad promedio de desplazamiento del equipo de picking. Respecto a la función de penalización por anticipación o demora en el cumplimiento del plazo para finalizar el armado de cada pedido, α es la penalización por unidad de tiempo en que se anticipa el armado de un pedido. β es la penalización por unidad de tiempo en que se retrasa el armado de un pedido. E_i es la cantidad de tiempo en que se anticipa al plazo el armado del pedido i. Y T_i es la cantidad de tiempo en que se retrasa el armado del pedido i. Donde $E_i = max\{0, t_i - c_i\}$ y $T_i = max\{0, c_i - t_i\}$. Y siendo c_i el tiempo de finalización efectiva para el pedido i, que se define como el tiempo en el que todos los artículos del pedido i son recogidos y devueltos al área de despacho. El conjunto de restricciones (2) no permite que el peso de los artículos de un lote determinado exceda la capacidad de cada equipo de picking. El conjunto de restricciones (3) indica que cada posición de almacenamiento no sea visitada más de una vez en cada lote r. El conjunto de restricciones (4) asegura que todos los equipos de picking salgan y regresen al área de preparación para despacho. El conjunto de restricciones (5) y (6) preservan el flujo. Si el equipo de picking k recoge el artículo l en el lote r, antes tiene que haber recogido al artículo h. Y si el equipo de picking k recoge el artículo h en el lote r, antes tiene que haber recogido al artículo l. La restricción (7) indica que se cumpla con la cantidad pedida por todos los clientes del artículo p. La restricción (8) indica

que se cumpla con la cantidad pedida de todos los artículos, por el cliente i. Las restricciones (9) y (10) imponen las condiciones sobre los valores de las variables.

4 Método de resolución

La teoría computacional clasifica a estos problemas con una complejidad NP-Hard. Es decir, que se pueden resolver de forma exacta solo en instancias muy pequeñas. Dada la intratabilidad de este problema, se requiere de algoritmos no deterministas para resolverlo en tiempos polinomiales. Por esta razón se propone un algoritmo evolutivo para resolver este problema. Se utiliza una representación del tipo permutación de enteros, muy común en problemas de optimización combinatoria como este. Se usa una representación con un cromosoma compuesto por dos genomas. Para explicar la representación veamos mediante un ejemplo muy simple, cómo se codifica una solución a partir de tres pedidos de entre los que se identifican solicitudes de cuatro artículos diferentes. En la Tabla 1, se muestra la información respecto a los pedidos ingresados. Puede verse que el pedido 1 está constituido por 3 artículos (una unidad del tipo A y dos unidades del tipo C), el pedido 2 por 5 artículos (una unidad de A, una de B, dos de C y una de D) y el pedido 3 por 4 artículos (dos unidades de B y dos de D).

Tabla 1. Ejemplo para el OBP+OPP

Pedidos	**Artículos**				**Total**
	A	**B**	**C**	**D**	
1	1	0	2	0	3
2	1	1	2	1	5
3	0	2	0	2	4
Total	2	3	4	3	12

Para codificar esta información, la ordenamos en dos filas, una para los artículos (y se identifica el pedido al que corresponde cada artículo) y otra para asociar un número entero a cada uno de los artículos (Tabla 2).

Tabla 2. Codificación

Artículos (Pedido al que pertenece)											
A(1)	A(2)	B(2)	B(3)	B(3)	C(1)	C(1)	C(2)	C(2)	D(2)	D(3)	D(3)
↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
1	2	3	4	5	6	7	8	9	10	11	12

Luego, se diseña un cromosoma con dos genomas (Tabla 3) que tiene en cuenta la codificación de la Tabla 2.

Cromosoma: {[G1] [G2]}

Genomas:

[G1]: Secuencia en que se recogerán los artículos en el almacén.

[G2]: Secuencia de posiciones en el [G1] de finalización de cada lote.

Dimensiones:

[G1]: Número total de artículos $\sum_{i\in\mathcal{I}} Q_i$.

[G2]: Número total de artículos $\sum_{i\in\mathcal{I}} Q_i$ (el límite corresponde a lotes de un solo artículo).

Tabla 3. Cromosoma = Genoma 1 + Genoma 2

Genoma 1												
Posiciones →	1	2	3	4	5	6	7	8	9	10	11	12
[G1] →	6	7	9	10	11	1	3	2	12	4	8	5
	lote 1					lote 2		lote 3				
Genoma 2												
[G2] →	5	7	12	-	-	-	-	-	-	-	-	-

La secuencia en que se recogerán los artículos correspondientes a cada lote es la siguiente, lote 1: {6→7→9→10→11}, lote 2: {1→3} y lote 3: {2→12→4→8→5}. Esto indica, por ejemplo, que para el lote 2, el equipo de picking debe ir a la posición de almacenamiento del artículo 1 (A(1)), luego se debe ir a la posición de almacenamiento del artículo 3 (B(2)) y finalmente ir al área de despacho y colocar cada artículo en el lugar del área de almacenamiento donde se están armando los pedidos. En la figura 1 se muestran los recorridos que realizarán los equipos de picking. Este tipo de representación permite lograr mayores niveles de eficiencia en este tipo de problemas y da la posibilidad de incorporar de manera directa conocimiento específico del problema, lo que da mayor flexibilidad a la representación y facilita la consideración de restricciones en el espacio de búsqueda. Por otro lado, la factibilidad de los individuos respecto a los conjuntos de restricciones (2) - (8) están garantizados por la representación. En la inicialización, se busca la mayor variedad posible generando la población inicial de forma aleatoria y se utiliza un criterio de terminación enfocado al costo, que limita el número máximo de iteraciones. El proceso de búsqueda es dirigido mediante el criterio de selección favoreciendo los individuos más aptos. Para ello se utiliza la técnica de selección por torneo en la que cada individuo se toma eligiendo el mejor de un conjunto de *k* individuos tomados al azar de la población actual [24]. Esto se repite iterativamente hasta completar la muestra. Los operadores genéticos son aplicados al Genoma 1. Se utiliza un operador de cruce Edge Recombination Operator [25] y un operador de mutación de inserción [26]. El Genoma 2 se completa de acuerdo a la capacidad del equipo de Picking. El seudo-código del algoritmo propuesto se presenta en la figura 2.

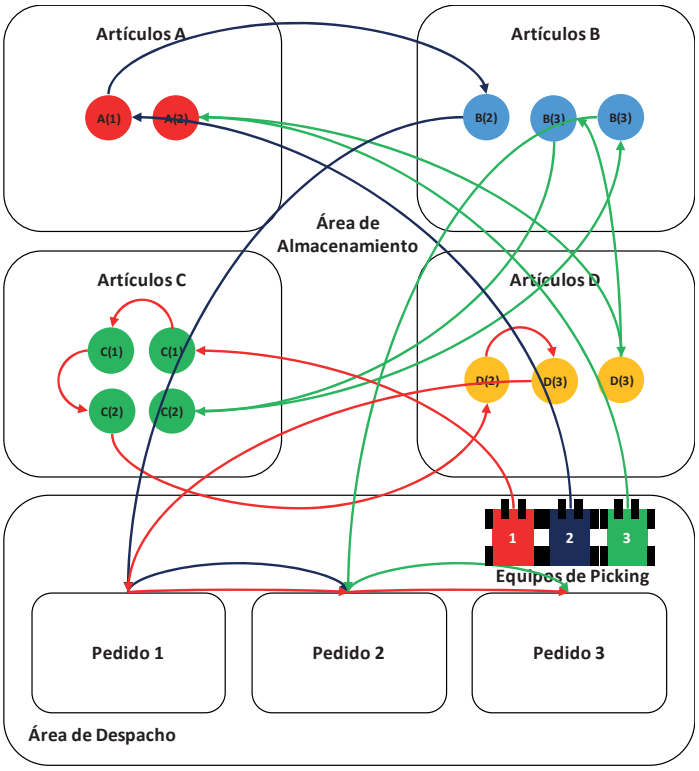

Fig. 1. Recorridos de los equipos de picking

```
1: Load Input          % información de Pedidos, lay-out y parámetros del algoritmo.
2: nLot ← nLotMin
3: while nLot < nLotMax
4:   t ← 0;
5:   P(t) ← InitPop(Entrada);
6:   FitP(t) ← EvalPop(P(t));
7:   For t ← 1 a MaxNumGen
8:       Q(t) ← SelecBreeders (P(t), FitP(t));
9:       Q(t) ← Crossover(Q(t));
10:          Q(t) ← Mutation(Q(t));
11:          FitQ(t) ← EvalPop(Q(t));
12:          P(t) ← SelSurviv(P(t), Q(t), FitP(t), FitQ(t));
13:          FitP(t) ← EvalPop(P(t));
14:          if TermCond(P(t), FitP(t))
15:              break;
16:      end
17:      end
18: nLot ← nLot +1;
18: end
```

Fig. 2. Seudo-código del algoritmo propuesto

5 Experimento computacional

Con el propósito de evaluar la calidad de las soluciones y el rendimiento del algoritmo propuesto se utilizaron las instancias propuestas en [11]. Se resolvieron tres instancias. Una instancia mediana (DS1/M1), una grande (DS2/M1) y una muy grande (DS3/M1) (Tabla 4).

Tabla 4. Características de las instancias [11]

	DS1/M1	**DS2/M1**	**DS3/M1**
Número de pedidos	40	80	200
Número de artículos diferentes	80	160	300
Peso total medio (kg.)	13.704	37.152	158.784
Capacidad del equipo de picking (kg.)	10.000	10.000	20.000

Para las instancias, se suponen las siguientes distribuciones de probabilidad. La cantidad del artículo p en el pedido del cliente i sigue una distribución uniforme entre 1 y 10, es decir, $q_{i,p} \sim U(1, \dots, 10)$. El número de artículos diferentes en el pedido de un cliente i sigue una distribución normal, con media 10 y desviación estándar 5, es decir $|\mathcal{P}_i| \sim N(10,5)$. El plazo en el que debe estar finalizado el armado de un pedido i, sigue una distribución uniforme, estos momentos se consideran discretizados en segundos y están entre las 10:00 am y las 18:00 pm, esto es, $t_i \sim U(36000, \dots, 64800)$. El peso unitario de cada artículo p, sigue una distribución uniforme entre 8 y 24 kg., es decir, $w_p \sim U(8, \dots, 24)$. Respecto a los parámetros de los equipos de picking, se supone una velocidad promedio de desplazamiento de $v = 2\ m/s$, un tiempo medio para la recolección de cada artículo de $t_{pick} = 15$ seg., un costo de desplazamiento por unidad de tiempo de $\varsigma = 0{,}05$ u.m. y una capacidad de carga (Cap) que depende del tipo de instancia que se esté considerando. En cuanto a los parámetros de la función objetivo, se considera una penalización por unidad de tiempo de anticipación en el plazo para el armado de un pedido de $\alpha = 0.5$ y una penalización por unidad de tiempo de demora en el cumplimiento del plazo para la finalización en el armado de un pedido de $\beta = 1$. Se utilizará la estrategia para acotar el espacio de búsqueda propuesta en [11] con el objetivo de que el desempeño del algoritmo sea comparable con los resultados obtenidos en esta publicación. Esto es, determinar un límite inferior, $|\mathcal{R}|_{min}$, y un límite superior, $|\mathcal{R}|_{max}$, para la cantidad de lotes en los que se agrupan los artículos a recoger, es decir, $|\mathcal{R}|_{max} \leq |\mathcal{R}| \leq |\mathcal{R}|_{min}$. Estos límites están dados por $|\mathcal{R}|_{min} = (\varphi_1 \cdot \sum_{p \in \mathcal{P}} w_p)/Cap$ y $|\mathcal{R}|_{max} = (\varphi_2 \cdot \sum_{p \in \mathcal{P}} w_p)/Cap$. Donde φ_1 y φ_2 son constantes decididas por los usuarios, y $\varphi_2 \geq \varphi_1$. El número máximo de iteraciones se fijó 500, el tamaño de la población en 150, el tamaño del torneo en 2, los parámetros de los límites del espacio de búsqueda $\varphi_1 = 2$ y $\varphi_2 = 4$, la probabilidad de cruce en 0.9, la probabilidad de mutación 0.15, la cantidad de individuos que pertenecen a la elite es el 5% de la población. Se utilizará una PC con un procesador Intel Core i7 3.00 GHz y 8 GB de RAM.

6 Resultados

En esta sección se presentan los resultados obtenidos con el algoritmo propuesto al resolver las instancias DS1/M1, DS2/M1 y DS3/M1. Los mismos se compararon con los resultados extraídos de [11] (Tabla 5, D_{Total}: Distancia total (metros); n_{Lot}: Número óptimo de lotes (cantidad); $D_{Promedio}$: Distancia promedio (metros); D_{σ}: Desvío estándar (metros); T_{Demora}: Tiempo de demora en el armado de los pedidos (segundos); C_{Total}: Costo total (unidades monetarias); $T_{CPU\ promedio}$: Tiempo de corrida en CPU promedio (segundos). Se realizaron 30 corridas para cada una de las instancias.

Tabla 5. Resultados

	Resultados extraídos de [11]			**Algoritmo Evolutivo**		
	DS1/M1	**DS2/M1**	**DS3/M1**	**DS1/M1**	**DS2/M1**	**DS3/M1**
D_{Total}	1304.00	3569.00	16945.00	1266.00	3215.00	14548.00
n_{Lot}	8.00	11.00	27.00	8.00	12.00	27.00
D_{Media}	163.00	324.46	627.59	158.25	267.91	538.81
D_{σ}	3.70	25.17	18.69	2.90	23.41	21.75
T_{Demora}	1181.00	4704.00	15481.00	1158.70	4801.91	15621.31
C_{Total}	1092.60	3104.83	9207.13	1090.78	2961.89	8898.01
$T_{CPU\ promedio}$	753.60	2629.90	5785.50	605.70	2121.90	4474.20

La D_{Total} mejora en todas las instancias (DS1/M1, DS2/M1 y DS3/M1, 2.91%, 9.92% y 14.15%, respectivamente). Para las instancias DS1/M1 y DS3/M1, el n_{Lot} fue el mismo que en el caso de los resultados extraídos de [11], mientras que en la instancia DS2/M1 el n_{Lot} fue mayor. Para la instancia DS1/M1, el T_{Demora} mejora en un 1.89%, mientras que en las instancias DS2/M1 y DS3/M1 empeora en 2.08% y 0.91% respectivamente. Finalmente, el $T_{CPU\ promedio}$ en todas las instancias fue menor. En resumen, en la figura 3, se muestran las mejoras porcentuales obtenidas con el algoritmo propuesto en este trabajo con respecto a los resultados extraídos de [11].

7 Conclusiones

En este trabajo se presentó un algoritmo evolutivo para resolver de manera combinada el Order Batching Problem y el Order Picking Problem. El algoritmo propuesto para resolver el problema, presentó un novedoso criterio de representación con dos genomas, que permite la incorporación directa de conocimiento específico del problema, dando mayor flexibilidad y facilitando la consideración de restricciones en el espacio de búsqueda. El algoritmo fue testeado en instancias simuladas de distintos tamaños. Se observó que el algoritmo propuesto mejoró los resultados extraídos de [11]. A partir de este trabajo, se presenta como línea futura de investigación, la consideración de este problema bajo una plataforma cross-dock y se le dará un abordaje multi-objetivo.

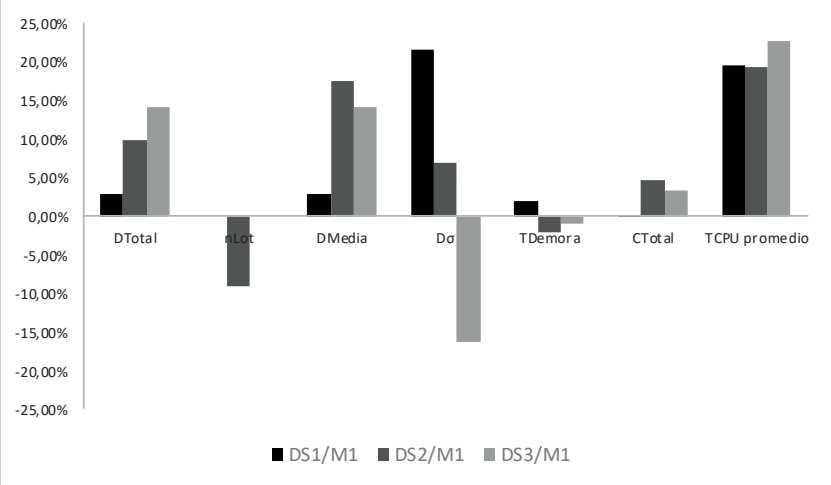

Fig. 3. Mejoras % con respecto a los resultados extraídos de [11]

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Una Metaheurística de Recocido Simulado para Resolver un Problema de Ruteo de Vehículos en la Recolección de Residuos

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Resumen. La gestión de la recolección de Residuos Sólidos Urbanos es una tarea compleja que deben enfrentar los gobiernos locales, consumiendo gran parte de su presupuesto. La utilización de herramientas computacionales que sirvan de apoyo a la toma de decisiones puede contribuir a mejorar la eficiencia del sistema y disminuir los costos asociados. En el presente trabajo se propone un algoritmo de recocido simulado para abordar el problema del diseño de las rutas de vehículos de recolección de residuos. El algoritmo propuesto es comparado contra otros dos algoritmos metaheurísticos: un algoritmo *Large Neighborhood Search* (LNS) de la literatura y un algoritmo genético estándar. La evaluación se realiza sobre instancias reales de la ciudad de Bahía Blanca y sobre *benchmarks* de la literatura. El algoritmo propuesto fue capaz de resolver todas las instancias planteadas teniendo un desempeño similar al LNS, mientras que el algoritmo genético estándar evidenció peores resultados.

Keywords: Residuos Sólidos Urbanos, Ruteo de Vehículos, Recocido Simulado.

1 Introducción

La generación de residuos sólidos urbanos (RSU) es una consecuencia inalienable del desarrollo de las ciudades modernas. Asimismo, su correcta gestión es uno de los elementos claves para el desarrollo sustentable de una ciudad [1]. Las etapas en la cadena logística inversa de los RSU son diversas. Según [2] pueden clasificarse en generación de residuos; manejo, separación, acumulación y procesamiento de residuos en origen; prosiguiendo la recolección; transferencia y transporte; separación, procesamiento y transformación de residuos sólidos; y disposición final. En dichas etapas existe una gran cantidad de decisiones que deben tomarse. Por este motivo, proponer herramientas informáticas que permitan asistir a los agentes tomadores de decisiones puede colaborar en un uso más eficiente de los recursos.

El presente trabajo se enfoca en la etapa de recolección; transferencia y transporte de residuos. Particularmente, se propone un algoritmo metaheurístico basado en recocido simulado para resolver este problema. El algoritmo propuesto es comparado contra otros algoritmos metaheurísticos de la literatura a los efectos de explorar su

performance. La experimentación es realizada en instancias reales de la ciudad de Bahía Blanca, Argentina, así como en conocidos *benchmarks* de la literatura.

El presente artículo se encuentra estructurado de la siguiente forma. En la Sección 2 se presenta el problema abordado y una revisión bibliográfica de los principales trabajos relacionados, en la Sección 3 se proponen los algoritmos de resolución utilizados, en la Sección 4 se desarrolla la experimentación computacional y, finalmente, en la Sección 5 se presentan las principales conclusiones de este trabajo.

2 Problema abordado

La gestión de los residuos sólidos urbanos en la ciudad de Bahía Blanca es una actividad crucial para las autoridades locales, no sólo por el amplio impacto ambiental y social asociado a su operatoria sino también porque consume una gran parte de los recursos presupuestarios del municipio [33]. Por lo tanto, enfoques que permitan optimizar la logística de recolección pueden ser relevantes para lograr una prestación más eficiente del servicio [17]. En este marco es que se han realizado propuestas para migrar desde el actual sistema de recolección puerta a puerta a un sistema contenedorizado [17,33]. Continuando con estos estudios, en la siguiente sección se presenta un modelo matemático para planificar la siguiente etapa en la cadena logística inversa de los residuos sólidos urbanos: el diseño de las rutas de recolección de los residuos acumulados en los contenedores. Asimismo, se realiza una revisión de los principales trabajos relacionados de la literatura.

2.1 Modelo matemático

El problema de recolectar lo acumulado en los contenedores de residuos se puede asemejar a un problema de enrutamiento de vehículos con restricción de capacidad (CVRP, por sus siglas en inglés, *Capacitated Vehicle Routing Problem*). El mismo puede modelarse matemáticamente de la siguiente forma. Dado un conjunto de contenedores C y un superconjunto $\underline{C} = C \cup c_0$, donde c_0 es el depósito donde inician y finalizan su recorrido los vehículos, se definen las siguientes variables y parámetros. La variable binaria x_{ij} que adopta el valor 1 si un vehículo utiliza el camino desde el contenedor $i \in C$ al contenedor $j \in C$, 0 en caso contrario y la variable continua positiva u_i que indica la carga del vehículo antes de llegar al contenedor $i \in C$. Luego se definen los parámetros Q como la capacidad del vehículo, d_{ij} como la distancia entre los contenedores $i \in I$ y el contenedor $j \in I$ y q_i como la cantidad de residuo a recolectar en el contenedor $i \in I$. De esta forma, se plantea el siguiente modelo, utilizando la formulación de dos-índices propuesta por [3] en las Ecuaciones (1)-(6).

$$\text{Minimizar } FO = \sum_{i,j \in \underline{C}} x_{ij} d_{ij} \tag{1}$$

Sujeto a:

$$\sum_{j \in \underline{C}} x_{ij} = 1, \ \forall \ i \in C \tag{2}$$

$$\sum_{j \in \underline{C}} x_{ji} = 1, \ \forall \ i \in C, \tag{3}$$

$$u_j - u_i \leq Q\left(1 - x_{ij}\right) - q_j, \ \forall \ i,j \in \underline{C} \tag{4}$$

$$q_i \leq u_i \leq Q, \ \forall \ i \in C \tag{5}$$

$$x_{ij} \in \{0,1\}, \ \forall \ i,j \in \underline{C} \tag{6}$$

El objetivo planteado consiste en minimizar la distancia total recorrida expresada en la Ecuación (1). Las Ecuaciones (2) y (3) garantizan que cada contenedor sea visitado una única vez, teniendo un único contenedor sucesor y un único contenedor predecesor en la ruta. La Ecuación (4) impide la formación de *subtours*. La Ecuación (5) garantiza que la capacidad del vehículo no sea sobrepasada. La Ecuación (6) establece la naturaleza binaria de la variable x_{ij}.

2.2 Revisión bibliográfica

El problema de recolección de residuos contenedorizados en una ciudad ha sido abordado frecuentemente en la literatura En [4] y [5] se desarrollan extensas revisiones sobre estos trabajos.
En el caso de Argentina pueden encontrarse algunos trabajos sobre aplicaciones de modelos VRP para resolver el problema de diseño de rutas de recolección. Por ejemplo, en [6] y [7] se implementan modelos de programación matemática para planificar las rutas de recolección de contenedores de residuos en la zona sur de la Ciudad de Buenos Aires. Por otro lado, en [8] se trabaja optimizando las rutas en esta zona teniendo como objetivos minimizar las distancias de recorrido simultáneamente con la minimización del desgaste de los vehículos. En la ciudad de Concordia, [9] presenta una aplicación para diseñar las rutas de recolección de la ciudad haciendo un esfuerzo por minimizar la cantidad de giros para facilitar la implementación de las rutas por las autoridades. Por otra parte, [10] exhibe un algoritmo para resolver la zonificación de la ciudad de San Miguel de Tucumán a los efectos de optimizar el uso de recursos, reasignando camiones hacia la zona céntrica de la ciudad. En [11] y [12] mediante modelos de programación entera se planifica la recolección de residuos reciclables en la ciudad de Morón. En [13] se presenta un enfoque integral que determina la localización de los contenedores, así como el diseño de la ruta que efectúa la recolección de su contenido en instancias simuladas de Bahía Blanca. En la misma ciudad, [14] y [15] exponen modelos de ruteo de vehículos con balanceo de distancias entre las distintas rutas para diseñar los recorridos de los recolectores informales de residuos reciclables.

3 Método de resolución propuesto

Como se mencionó anteriormente, la recolección de RSU en contenedores constituye un caso de aplicación del problema VRP (*Vehicle Routing Problem*). En teoría de complejidad computacional, este tipo de problemas están clasificados como NP-hard [16], es decir, es a lo sumo tan difícil como los problemas para los cuales no se han desarrollado aún algoritmos de resolución eficientes que se ejecutan en tiempo polinomial con respecto al tamaño del problema [17]. En este tipo de problemas las herramientas metaheurísticas permiten obtener buenas soluciones en tiempos de cómputo razonables. El algoritmo de resolución que se propone se basa en una estrategia de recocido simulado (SA, *Simulated Annealing* en inglés) y fue adaptada de los trabajos [18] y [19]. SA es un método basado en la búsqueda local que se desarrolló a partir de una analogía con el fenómeno físico de recocido [20] para resolver problemas complejos de optimización. Los métodos de búsqueda local buscan la solución con un mejor valor del criterio elegido en el entorno de la solución actual, la aceptan como la solución actual y repiten este procedimiento hasta que no resulte posible mejorar la solución en el entorno explorado. Mediante la aplicación sistemática de este procedimiento se obtiene, en general, un óptimo local para el problema. Para evitar quedar atrapado en un óptimo local, se debe incorporar un mecanismo de diversificación con el fin de explorar adecuadamente el espacio de soluciones. En la metaheurística de recocido simulado, la estrategia de diversificación permite movimientos, con cierta probabilidad, hacia soluciones que empeoran el valor actual de la función objetivo.

Para obtener una buena aproximación a la solución óptima del problema durante el proceso de búsqueda, resulta necesario reiniciar la búsqueda regularmente desde una de las soluciones aceptadas durante el proceso de búsqueda seleccionada al azar. El algoritmo SA incorpora los parámetros clásicos del recocido simulado. Seguidamente se indican los parámetros y variables correspondientes al algoritmo SA implementado.

- t : iteración actual.
- S_0 : solución inicial.
- S_A : solución actual.
- S_c : solución candidata.
- $V(S)$: entorno de la solución S, dado por el conjunto de soluciones que pueden obtenerse a partir de S mediante un movimiento o perturbación elemental.
- T : parámetro de control (que simula la temperatura en el proceso físico del recocido). Es un valor positivo que varía desde un valor inicial mayor, T_0, a otro que es menor, T_f, durante la ejecución del algoritmo.
- N_T : número de iteraciones realizadas por el algoritmo para cierto valor de T.
- $\alpha(T)$: función que determina el mecanismo de enfriamiento, es decir, la evolución de T durante la ejecución del algoritmo. En general, $\alpha(T) = \alpha T$, en la práctica $\alpha \in [0,8; 0,99]$.
- N_{cont} : número de iteraciones sin mejora en la iteración t.

- N_{stop} : número máximo de iteraciones permitidas sin mejora.

Se aplica el siguiente pseudo-código para determinar una solución potencialmente óptima.

Algoritmo de Recocido Simulado

i. Inicialización

Se utiliza un procedimiento constructivo aleatorizado para generar una solución inicial, S_0.
Se evalúa la función objetivo, $FO(S_0)$, empleando la Ecuación (1).
S_0 se adopta como solución actual S_A, $N_{cont} = t = 0$, $T = T_0$.

ii. Iteración t

Se genera aleatoriamente una solución candidata en el entorno de S_A, S_c $V(S_A)$.
Se evalúa $FO(S_c)$.
Se calcula $FO = FO(S_c) - FO(S_A)$.
Si $FO \leq 0$, $S_A = S_c$, $N_{cont} = 0$. *Obs: la nueva solución es aceptada.*
En otro caso, $p_A = e^{-\frac{FO}{T}}$. *Obs: la nueva solución es aceptada con probabilidad* p_A.
Se genera un número aleatorio uniformemente distribuido en el intervalo [0;1]:
Si $\leq p_A$, $S_A = S_c$, $N_{cont} = 0$;
En otro caso, $N_{cont} = N_{cont} + 1$.

$$t = t + 1$$

Si t es un múltiplo de N_T, entonces $T = \alpha(T)$
Si $N_{cont} = N_{stop}$ o $T \leq T_f$, se detiene la ejecución.

3.1 Metaheurísticas de comparación

Las metaheurísticas de comparación son el algoritmo de *Large Neighborhood Search* (LNS) desarrollada por Erdoğan [21] y un algoritmo genético estándar.

La metaheurística de Erdoğan fue adaptada a partir de la heurística conocida como *adaptative* LNS desarrollada por Pisinger y Ropke [22] que extiende la heurística original de Shaw [23]. Una explicación simplificada de su funcionamiento y pseudo-código (ver Fig. 1) puede consultarse en [24].

El funcionamiento de la heurística está constituido por dos etapas principales. La primera, es la construcción de una solución inicial que se obtiene insertando clientes en las rutas disponibles de acuerdo con el objetivo a minimizar (operador Sol-Inicial). Luego, se realiza una mejora mediante el operador *Local-Search* que aplica cuatro técnicas de búsqueda local. Las primeras tres son conocidas como Exchange (se intercambian dos clientes), 1-OPT (se extrae un cliente de una ruta y reinserta en otra) y 2-OPT (se intercambian dos segmentos de rutas). Estos operadores se encuentran detallados en [25]. El cuarto operador de búsqueda local es *Vehicle-Exchange*. Este operador intenta intercambiar los vehículos asignados a dos rutas, por lo cual es útil cuando se trabaja con flota heterogénea.

La segunda etapa es donde se intenta obtener un mejoramiento de la solución de la etapa anterior. Se aplica, el operador *Destroy-And-Rebuild* que altera de manera considerable la solución actual para explorar otra región del espacio de búsqueda y así poder escapar de óptimos locales. Particularmente, se extraen tramos extensos de

rutas de la solución actual y los clientes extraídos vuelven a reinsertarse en aquellas posiciones que minimicen la función objetivo (*Cost*). Una solución es aceptada si tiene un mejor costo que la mejor solución hallada hasta el momento o, en caso de que una solución no tenga mejor costo que la solución anterior, puede incluso ser aceptada con una probabilidad *p-value*. Este proceso se repite cíclicamente hasta el límite temporal impuesto por el usuario.

```
1: procedure LNS(input)          ▷ Como input se ingresa la información
   correspondiente a los clientes, vehículos y lugares de descarga (depots)
2:     S ← SolInicial()
3:     S' ← LocalSearch(S)
4:     BestS ← S'
5:     repeat
6:         S' ← DestroyAndRebuild(S')
7:         S' ← LocalSearch(S')
8:         if (Cost(S') <= Cost(S')) then
9:             BestS ← S'
10:        else
11:            p ← Random(0, 1)
12:            if (p <= pvalue) then
13:                S' ← BestS
14:            end if
15:        end if
16:    until Time elapsed > Time limit
17:    return BestS
18: end procedure
```

Fig. 1. Algoritmo LNS implementado en [21]. Fuente de la imagen: [24].

El algoritmo genético genérico fue desarrollado utilizando el *framework Distributed Evolutionary Algorithms in Python* (DEAP) [26]. Este posee las siguientes características:

Representación de las soluciones. Las soluciones se codifican como una permutación de enteros de longitud igual al número de contenedores *n*. Cada índice en el vector representa el orden de visita en el recorrido y el valor entero correspondiente representa uno de los contenedores.

Inicialización. La población de tamaño #*P* se inicializa aplicando un procedimiento aleatorio para generar las permutaciones con una distribución uniforme.

Operadores genéticos. El operador de recombinación es el *Crossover* parcialmente mapeado (PMX) aplicado sobre dos individuos seleccionados con probabilidad p_c. El operador de mutación se basa en *Swap Mutation* e intercambia dos elementos de la permutación. La mutación se aplica a un individuo con probabilidad p_m. Los operadores propuestos garantizan la factibilidad de la solución.

Selección, La selección es realizada a través de un torneo binario, de los cuales se selecciona el de mejor fitness.

Reemplazo. En cada iteración la población nueva está conformada por el mejor 10 % (con mejor *fitness*) de la población anterior y el resto por individuos nuevos generados a través de los operadores genéticos.

Evaluación de *fitness*. La función de *fitness* es decodificada leyendo los alelos de izquierda a derecha e insertando una visita al depósito cuando es necesario.
Análisis paramétrico. Los parámetros que fueron analizados mediante un análisis estadístico fueron el tamaño de la población $\#P$ -se consideraron los valores 100; 150 y 200- la probabilidad de mutación p_m -se consideraron los valores 0,05; 0,1; 0,15; 0,20 y 0,25- y de cruzamiento p_c -se consideraron los valores 0,5; 0,6; 0,7; 0,8; 0,9 y 1-. Los análisis paramétricos se realizaron sobre las instancias P-n16-k8, P-n19-k2 y P-n20-k2 propuestas en [27]. Para cada instancia y para cada configuración paramétrica se realizaron 50 ejecuciones independientes. Se aplicó la prueba de Shapiro-Wilk para estudiar si la distribución de fitness tenía una distribución normal. Debido a que numerosas ejecuciones no se ajustaron a una distribución normal se evaluaron las medianas a través de la prueba de Friedman, seleccionándose la siguiente configuración: $\#P = 200$, $p_c = 0{,}9$ y $p_m = 0{,}25$.
Corte por estancamiento. Se incorporó un mecanismo de corte por estancamiento. El algoritmo se detiene cuando no se obtiene ninguna mejora en el fitness del mejor individuo durante un intervalo de tiempo igual al 50% del tiempo máximo de ejecución (Eq. (7)) de la instancia. En caso contrario, continúa hasta efectuar la generación –ciclo evaluación, selección, cruzamiento, mutación y reemplazo- que al finalizar haya sobrepasado el tiempo máximo de ejecución.

4 Resultados

Los resultados obtenidos corresponden a la resolución de cuatro escenarios reales de la logística de recolección de RSU de Bahía Blanca construidos en los trabajos [28] y [29]. Asimismo, la experimentación correspondiente a los enfoques metaheurísticos fue ampliada con la resolución problemas de un *benchmark* de la literatura.

4.1 Pruebas realizadas sobre escenarios reales

Los escenarios planteados en [28] y [29] constituyen casos reales diseñados en función del problema de RSU existente en la ciudad de Bahía Blanca.

Se estudian dos planificaciones distintas para la disposición de los contenedores, considerando la recolección de ambas fracciones de residuos: tanto los secos como los húmedos. Dichas planificaciones contemplan dicha opción de separar los contenedores en residuos húmedos y secos a la vez que consideran la opción de utilizar diferentes frecuencias de recolección. Las planificaciones difieren fundamentalmente en cuanto a la frecuencia con la cual se plantea recolectar los residuos secos, conformándose de esta manera los siguientes cuatro escenarios:

Escenario 1:
- Frecuencia de recolección [veces/semana]: 6.
- Tipo de residuo a recolectar: húmedo.

Escenario 2:
- Frecuencia de recolección [veces/semana]: 4.
- Tipo de residuo a recolectar: seco.

Escenario 3:

- Frecuencia de recolección [veces/semana]: 6.
- Tipo de residuo a recolectar: húmedo.

Escenario 4:

- Frecuencia de recolección [veces/semana]: 3.
- Tipo de residuo a recolectar: seco.

Resulta necesario aclarar que las diferencias indicadas entre los distintos escenarios repercuten esencialmente en la cantidad de contenedores que se utilizarán, sin embargo, la explicación de este hecho no forma parte de los objetivos planteados para este trabajo.

Para la resolución exacta se implementó mediante el software CPLEX versión 12.6.0.0 en un entorno de GAMS, utilizando la versión de paralelismo oportunista de dicho software, con la adición de la inecuación válida del mínimo número de viajes para acelerar la convergencia. Se fijó un límite de tiempo para cada ejecución de 15 000 segundos.

Tanto el algoritmo de *SA* como el de LNS fueron programados mediante la interfaz de *Visual Basic for Applications* (VBA) de MS Excel. Mientras que, para llevar a cabo el algoritmo de GA, fue utilizada la librería DEAP y se empleó Python como lenguaje de programación.

Cada algoritmo se ejecutó en distintos computadores personales, realizando 50 corridas para cada instancia con el fin de obtener una muestra más representativa del rendimiento de los algoritmos.

Los resultados obtenidos se exponen a continuación en las Tablas 1 y 2. En la primera se puede observar la mejor distancia -FO según Ec. (1)- obtenida para cada escenario de RSU con cada uno de los métodos propuestos de resolución. Para la solución de CPLEX, se reporta el *gap* calculado por el software, el cual indica que no se halló el valor óptimo en los escenarios 2 y 4. En la segunda tabla se contrastan tres indicadores de los conjuntos de soluciones obtenidos para cada metaheurística, una medida de centralización, como lo es el valor promedio de los resultados obtenidos, una medida de dispersión, esto es, el desvío estándar, y el *gap* promedio. El *gap* es calculado como la diferencia entre el valor promedio y el valor obtenido por CPLEX, dividida por este último.

Tabla 1. Resultados del problema de RSU: mejores soluciones de cada metaheurística.

Instancia	Resolución exacta CPLEX		Mejor resultado FO metaheurísticas		
	FO	CPLEX gap %	SA	LNS	GA
Escenario 1	22613,90	0,00	22814,00	22877,00	36712,00
Escenario 2	41533,28*	26,35	43763,00	43491,00	48561,00
Escenario 3	27150,00	0,00	27707,00	27648,00	49463,00
Escenario 4	62800,63*	18,33	65995,00	65938,00	71185,00

* Debido a que no se encontró la solución óptima para estos escenarios, los valores corresponden al mejor valor hallado por CPLEX para el tiempo de ejecución (*Upper Bound*).

Tabla 2. Resultados del problema de RSU: performance media de cada metaheurística.

Escenario	SA			LNS			GA		
	FO promedio	Desvío est.	gap %	FO promedio	Desvío est.	gap%	FO promedio	Desvío est.	gap%
Escenario 1	23310,12	216,82	3,08	23542,56	246,68	4,11	39041,70	1164,59	72,65
Escenario 2	44294,64	291,85	6,65	44229,92	303,77	6,49	51047,52	1247,72	22,91
Escenario 3	28143,00	296,63	3,66	28032,34	223,30	3,25	53408,00	1396,83	96,99
Escenario 4	66366,31	202,49	5,68	66356,19	180,61	5,66	73290,82	1096,94	16,70

El tiempo de ejecución máximo de todas las metehaurísticas se estableció proporcionalmente a la cantidad de nodos de la instancia -excluyendo al depósito- y deviene de la Ecuación (7).

$$Tiempo\ Máximo\ de\ Ejecución\ [seg] = \frac{(n°\ de\ nodos * 15 * 60)}{50} \quad (7)$$

Debe tenerse en cuenta que tanto el SA como el GA aquí descriptos cuentan con mecanismos de corte por estancamiento que pueden llevar a un tiempo real de ejecución sea inferior al máximo. Esto no es así para el LNS cuyo tiempo de ejecución será igual al máximo.

Si bien al momento de ejecutar los escenarios RSU en CPLEX se limitó el tiempo en 15 000 segundos, en los escenarios 1 y 3, en los que se alcanzó el valor óptimo, se hizo un corte de forma más temprana, habiendo consumido 1892 segundos en el primer escenario y 4367 segundos en el escenario 3.

A modo de evaluar su desempeño, en la Tabla 3 se registra la cantidad de iteraciones que requirió cada metaheurística en el tiempo establecido por la ecuación previamente mencionada.

Tabla 3. Tiempo e iteraciones promedio requeridos para los escenarios de RSU.

Escenario	Tiempo de cómputo máximo (en segundos)	Número promedio de iteraciones realizadas		
		SA	LNS	GA
Escenario 1	1242	76860,12	33700,22	30739,22
Escenario 2	1242	211455,16	16724,16	50439,62
Escenario 3	1422	265653,78	11563,00	51479,40
Escenario 4	1422	1516847,40	6129,72	63967,20

4.2 Pruebas realizadas sobre *benchmark* de la literatura

Para la ampliación de la comparación de metaheurísticas se utilizaron algunas instancias del conjunto de *benchmark* propuesto en [30], denominado Conjunto E. Tanto las instancias como las soluciones óptimas fueron descargadas del repositorio digital VRP-REP [32].
A continuación, se observa en la Tabla 4 los mejores resultados hallados en cada instancia por los algoritmos en estudio, mientras que en la Tabla 5 se ve reflejado el rendimiento de las metaheurísticas mediante los mismos parámetros utilizados para evaluar el desempeño en RSU.

Tabla 4. Resultados del conjunto E: mejores soluciones conocidas de cada metaheurística.

Instancia	Solución óptima	Mejor resultado FO metaheurísticas		
		SA	LNS	GA
E-n13-k4	247,00	247,00	247,00	247,00
E-n22-k4	375,00	375,00	375,00	375,00
E-n23-k3	569,00	569,00	619,00	569,00
E-n30-k3	534,00	503,00*	534,00	529,00*
E-n31-k7	379,00	379,00	379,00	427,00
E-n33-k4	835,00	835,00	835,00	859,00
E-n51-k5	521,00	521,00	521,00	582,00

* Las soluciones encontradas tienen un menor valor de FO, pero mayor cantidad de rutas (k = 4) que la solución de referencia, hecho que se observa también en la Tabla 5.

Tabla 5. Resultados del conjunto E: Performance media de cada metaheurística.

Instancia	SA			LNS			GA		
	FO	Desvío est.	*gap* %	FO	Desvío est.	*gap* %*	FO	Desvío est.	*gap* %
E-n13-k4	247,08	0,27	0,03	247,00	0,00	0,00	247,72	1,09	0,29
E-n22-k4	376,14	3,24	0,30	375,00	0,00	0,00	393,94	14,90	5,05
E-n23-k3	569,04	0,20	0,01	619,00	0,00	8,79	625,086	41,06	9,85
E-n30-k3	503,04	0,28	-5,80	535,08	1,45	0,20	583,86	36,37	9,34

E-n31-k7	394,34	13,11	4,05	379,64	2,16	0,17	485,44	31,18	28,08
E-n33-k4	836,44	2,21	0,17	835,00	0,00	0,00	903,42	23,11	8,19
E-n51-k5	522,48	3,81	0,28	521,84	2,76	0,16	645,56	29,05	23,91

* El *gap* fue calculado como la diferencia entre el valor promedio y el óptimo, dividida por este último.

Al igual que la Tabla 3, se registraron el promedio de iteraciones alcanzadas en cada metaheurística en el tiempo dado por la Ecuación (7).

Tabla 6. Tiempo e iteraciones promedio realizadas por instancia.

Instancia	Tiempo de cómputo máximo (en segundos)	Número promedio de iteraciones realizadas		
		SA	LNS	GA
E-n13-k4	216	76860,12	33700,22	30739,22
E-n22-k4	378	211455,16	16724,16	50439,62
E-n23-k3	396	265653,78	11563,16	51479,40
E-n30-k3	522	1516847,40	6129,72	63967,2
E-n31-k7	540	2390054,58	9992,40	6800,86
E-n33-k4	576	3614994,88	4502,92	68233,54
E-n51-k5	900	6460189,50	2788,66	91230,70

4.3 Análisis de resultados

A partir del análisis de los resultados se verifica que los tres procedimientos metaheurísticos resultan válidos para utilizarlos en la resolución de los problemas del tipo CVRP.

Es necesario aclarar que tanto SA como GA encuentran un valor menor al óptimo reportado en la bibliografía para la instancia E-n30-k3 dado que, al no contar con una restricción que indique el número de rutas, presentan una solución con una ruta adicional. Es por este motivo también que se ve observa un valor negativo del gap en dicha instancia dentro de la Tabla 5 para el SA.

La experiencia realizada sobre *benchmark* y posteriormente sobre los escenarios de RSU, marcó un buen rendimiento tanto del algoritmo propuesto SA como el LNS de la literatura al arrojar valores considerablemente pequeños del *gap* promedio. Por otra parte, GA mostró en comparación con el SA y el LNS un bajo rendimiento que se ve reflejado nuevamente en el *gap* promedio, posiblemente se deba a que se utilizó un algoritmo genético estándar con una función de decodificación simple tomada de aplicaciones en problemas irrestrictos como el Problema Agente Viajero.

En cuanto a las iteraciones promedio realizadas, se observa que SA y GA alcanzan mayor cantidad de iteraciones a medida que crece la cantidad de nodos, no sucede lo mismo en el caso de LNS para el que donde el número de iteraciones disminuye al aumentar la cantidad de nodos.

5 Conclusiones

Encontrar nuevas herramientas para volver más eficiente la logística de residuos sólidos urbanos (RSU) constituye una inquietud acuciante en las sociedades actuales. Este trabajo está centrado en la resolución de problemas de recolección de residuos para el área de Bahía Blanca. Particularmente se aborda una problemática encontrada en trabajos previos donde la resolución exacta de problemas de recolección de residuos resultaba ineficiente, debido a que se requería la partición de los escenarios en porciones más pequeñas para lograr la convergencia a una solución factible aceptable.

Por ello, en este trabajo se presenta un estudio comparativo entre la resolución exacta y tres herramientas metaheurísticas de resolución para el problema de la recolección de RSU en Bahía Blanca. La resolución exacta está basada en una formulación de programación matemática del modelo CVRP mediante el software CPLEX. Por otro lado, en lo que concierne a la resolución metaheurística se propone un algoritmo de recocido simulado que es comparado contra un algoritmo tomado de la literatura basado en *Large Neighborhood Search* (LNS) y un algoritmo genético estándar. Además, se extiende la comparación de las metaheurísticas con algunas instancias de un conocido *benchmark* de la literatura. El algoritmo de recocido simulado propuesto tiene un desempeño similar que el algoritmo LNS de la literatura -obteniendo en varias ocasiones valores cercanos a la solución óptima- y supera marcadamente al algoritmo genético estándar.

Luego del trabajo experimental realizado, se puede afirmar que la aplicación de estos algoritmos redunda en la obtención de resultados potencialmente aceptables y competentes, contando las metaheurísticas con la ventaja del menor esfuerzo de cómputo requerido para llegar a la solución.

Como líneas de trabajo a futuro se tiene previsto experimentar con escenarios de mayor tamaño de la ciudad Bahía Blanca, utilizando las metaheurísticas propuestas, que fueron validadas en el presente trabajo. Por otro lado, se propone continuar mejorando la formulación de programación matemática, implementada a través de CPLEX, mediante la inclusión de inecuaciones válidas adicionales que permitan reducir los tiempos de resolución. Además, se propone desarrollar la función de codificación del algoritmo genético con un enfoque que se adapte mejor al tipo de problema CVRP abordado.

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A Simulation-Based Optimization Framework for a Comparative Analysis of Different Heuristics Applied to Discrete-Event Simulation

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Abstract. This work presents a comparison framework to evaluate different optimization heuristics applied to discrete event simulation. The proposal incorporates variance reduction techniques and dynamic runs with the purpose of improving the heuristics' results and computational costs. The framework was tested on optimization problems based on two different discrete event simulation models and three different metaheuristics: simulated annealing, genetic algorithms, and tabu search. The implementation of the framework yields positive results in the search of the global optimums, especially for stochastic noise sensible algorithms such as simulated annealing.

Keywords: Simulation-based optimization · Comparative analysis · Variance reduction

1 Introduction

The use of optimization methods is a powerful tool to support decision making in any industry. At the same time, simulation techniques can be used to replicate real systems and evaluate different scenarios given the uncertainty and complexity faced by the decision-maker, without conducting expensive experiments.

The combination of simulation-based methods and optimization have been extensively used in the last decades for finding the best configurations and responses of complex systems. Despite the constant improvements of computational hardware, the lack of computational resources is still an issue for the implementation of these methods. Therefore, the utilization of techniques and algorithms that deal appropriately with the variability of the responses of real systems is a common subject of investigation for many researchers.

One of the main characteristics of simulation optimization is the black-box approach that must be used to search for local optimums. Since in most of the simulation models

a mathematical expression of the system is not available, strategies that evaluate only the input and responses of the model are necessary for the exploration of the search space of possible configurations for the system.

On the other side, the variability of the response of the model is an element that must be considered in the implementation of these techniques. Because of the stochastic nature of real systems, simulation-based methods replicate the variance of the processes that are being modeled. The latter gives simulation optimization another aspect that must be addressed: the costs of estimating the actual response of a specific configuration of the system. Because of the variability of the response, an estimation of the output is necessary to evaluate the objective function of the optimization problem. To improve the statistical significance of the estimation, additional runs of the model are needed to obtain an accurate value of the function, adding computational costs in the execution of the optimization method.

These two elements represent the main challenges of simulation-optimization techniques. While the black-box approach limits the available methods for solving the optimization, the stochastic nature of simulation adds additional computational costs for the evaluation of the objective function. These characteristics and the fact that the optimization problems usually have a large search space makes the heuristic methods that explore only a fraction of the search space a common choice for achieving positive results.

Also, these aspects justify the use of statistical techniques applied to the model to reduce the estimation error that may mislead the heuristic's exploration of the search space [10] while improving the operation and results of the optimization algorithms with limited computational costs. The presented work explores different techniques and optimization algorithms that contribute to this purpose.

The remainder of this paper is organized as follows. In Section 2 a literature review is conducted considering recent simulation optimization studies and similar proposals. Section 3 presents the optimization heuristics and statistical techniques used in the study. Section 4 describes the proposed framework that incorporated the described techniques and different post-optimization analysis. Section 5 shows the preliminary testing based on the execution of two test simulation models for each of the selected heuristics. Finally, section 6 presents the conclusions of the work and suggests future research lines.

2 Literature Review

The specialized literature presents many study cases of applications of simulation-based optimization using heuristics. Rezaeiahari and Khasawneh [18] propose a simulation-optimization approach to solve the scheduling problem of medical tourists who travel to destination medical centers (DMCs). In their work, the authors compare the performance of the two metaheuristics optimization procedures: simulated annealing and tabu search. Their approach considers a simulation evaluation at each iteration of the optimization process. The objective of the work is to determine the best schedules for the medical tourist considering their preferred hours and minimizing the total attention

times of the exams. Their results show low differences in the utilization of tabu search or simulated annealing.

Lu et al [14] propose a genetic algorithm-based simulation-optimization method to solve the integrated inventory management process that considers five different policies: schedule-based, cost-based, demand-based, schedule-cost-based, and schedule-demand-based policies. Their work aims to determine how much material to stock and different strategies for the prioritization of materials in the construction project to avoid delays. The authors test the proposed methodology in a set of fictitious project networks.

Another contribution to the literature is presented by Haddock and Mittenthal [7]. They propose a simulated annealing algorithm with a simulation model to determine the optimal parameter levels at which to operate a system. They present numerical testing of a hypothetical simulation model and provide recommendations for a proper parameter tuning of the algorithm.

Rabe et al. [16] also explore simulation-optimization implementations using dynamic runs and solution filters in discrete-event simulation while executing a genetic algorithm to solve a manufacturing case study. This work also has relevance to this study because of its focus on approaching the computational cost problem related to simulation-optimization methods.

We can also find contributions to the literature that explore variance reduction techniques. Abourik et al [1] explore the uses of the common random numbers technique with a simulation model, obtaining positive results on the variance reduction of the difference between configurations. Mawlana and Hammad [15] implemented the same technique to execute a preliminary study that determined the number of replications that a simulation model should execute in conjunction with a genetic algorithm. The authors [1,15] report savings of 58.8% and 80.97% in the simulation runs needed for achieving a certain variance level. Finally, the publication that shares the most common objectives with this work is the proposal of Anderson et al. [2], which explores the usage of the scatter search heuristic using common random numbers, antithetic variates, and dynamic runs in conjunction to improve the results of the optimization heuristic.

While Abourik et al [1], and Mawlana and Hammad [15] use the variance reduction techniques to conduct a preliminary study of the replications needed, Anderson et al. [2] implement these methods to dynamically save simulation runs in the execution of the algorithm. Nevertheless, none of these works explore the interactions of these techniques in a simulation-optimization context.

3 Heuristics and techniques

3.1 Optimization Heuristics

According to the objectives of this study, three metaheuristics that have been extensively used in the literature are considered in this work: simulated annealing, genetic algorithms, and tabu search, that are further described.

Simulated Annealing

Proposed by Kirkpatrick, et al [11], simulated annealing (SA) operates by emulating the thermodynamic process in which a system tries to find an equilibrium point that minimizes the total energy [4]. The algorithm operates evaluating a candidate configuration x_i' for the objective function $f(x)$ randomly selected from the neighborhood of the initial configuration x_i for each iteration i. The configuration x_i' is accepted as the initial configuration of the next iteration by the probability shown in Equation 1.

$$Pr\ (Acceptance) = \begin{cases} 1, & f(x_i) < f(x_i') \\ e^{\frac{f(x_i') - f(x_i)}{t}}, & \sim \end{cases} \quad (1)$$

Equation 1 shows that a better configuration is always selected while a worse configuration may be selected depending on the value of t, which represents the temperature of the iteration. The temperature t is determined by the temperature schedule which is the main parameter of the algorithm. This schedule is defined by the initial temperature, the final temperature, and how the temperature decreases in each iteration. There are different alternatives to define the cooling schedule. For instance, the geometric, reciprocal, and logarithmic schedules are common options [4]. Also, the algorithm includes a parameter n_{max} that defines the number of iterations before a temperature decrease is applied.

The chance of selecting a worse configuration is incorporated in the algorithm to escape local optimums in the exploration of the search space. As the search proceeds, the value of t decreases to the point that it is impossible to accept a worse configuration, or the termination criteria is met.

Genetic Algorithms

A genetic algorithm (GA) is an evolutionary strategy that uses population-based iterations to recombine and select the best configurations available. With the assumption that the configurations of the objective function can be expressed in bit strings [24], the metaheuristic works with two main operators: crossover and mutation. In analogy to the biological concepts in which the algorithm is based, the crossover operator recombines the population of individuals that represent a set of configurations for the objective function. This recombination is based on a fitness value that is obtained by the value in the objective function of each individual.

Once obtained the fitness values of the population, an intermediate population of the same size as the initial population is randomly created selecting individuals with replacement according to a selection function. There are two main ways to define the fitness values and select the individuals for the intermediate population: proportional fitness assignment and rank-based fitness assignment [22].

Then, the crossover operator is applied to the intermediate population, recombining random pairs of individuals with a probability given by a crossover parameter. If a pair

of individuals are selected to recombine, then they exchange portions of their binary strings selected by a random position.

The final step of the iteration is the mutation operator, which changes the value of one position of the binary string of the individuals randomly and according to a probability given by the mutation parameter.

Tabu Search

Tabu search (TS) is a metaheuristic procedure designed for escaping local optima, proposed by Glover [5]. The algorithm considers the evaluation of possible movements by changing one bit of the binary representation of the initial configuration. After the evaluation of each neighborhood, the algorithm chooses the best movement for the next iteration, even if it means a worse value for the objective function. For escaping local optima, the algorithm limits the possible movement with a tabu list of size given by the parameter tuning. The tabu list restricts the available movements, forcing to select the next best possible movement of the neighbors and can be ignored if an aspiration criterion is met. In this work, we consider as an aspiration criterion to allow a tabu active move only if the resulting solution is better than the best one found, as it is typically implemented in the literature [22].

3.2 Statistical Techniques

The three metaheuristics described in the previous section require an evaluation of the objective function $f(x)$ to determine the direction of the exploration of the search space defined by the decision variables of the optimization problem. Using simulation-based methods to model complex systems, an estimation $f_n(x)$ must be used to evaluate the objective function $f(x)$, where n is the number of runs of the simulation model. The number of replications n increase the computational costs of running the simulation model and therefore the costs of solving the optimization problem. Nevertheless, a small number of runs will increase the estimation error of $f_n(x)$, deviating the search heuristics of the correct direction.

For example, at the last iterations of the simulated annealing, the chance of selecting a worse configuration for the next iteration is almost zero, but if the estimation error is too large, then the algorithm may wrongly conclude that the new configuration is better than the initial configuration. The latter may mislead the heuristic and affect the performance of the algorithm.

Because of this, variance reduction techniques (VRT) that may operate in a discrete-event simulation are considered in this work. These techniques take advantage of the operation of the random numbers that define the probability distribution of the processes of the model to reduce the variance of the results, decreasing the estimation error of $f_n(x)$ without incurring additional computational costs.

Also, a dynamic criterion for selecting the number of runs is applied to reduce even more the computational costs of the heuristic's operation.

Common random numbers

Common random numbers (CRN) is a variance reduction technique that can be applied in discrete-event simulations by inducing a positive correlation between the results of two different configurations of a simulation model. The underlying concept behind this technique is evaluating configurations under similar experimental circumstances in a way that the differences of responses of the configurations are caused by differences of the configurations rather than the variability of the systems [13]. This is possible using the same random number for the same processes in each configuration evaluated: if a process uses a low random number in one configuration then every compared configuration will use the same low random number in the same moment of the process.

The variability reduction is achieved in the variance of the differences between configurations. Using the same random numbers, the response of the system is positively correlated. Equation 2 shows how a positive correlation causes a variance reduction of the differences

$$Var\left[\frac{\sum_{j=1}^{n} Z_j}{n}\right] = \frac{Var[Z_j]}{n} = \frac{Var(X_{1j}) + Var(X_{2j}) - 2Cov(X_{1j}, X_{2j})}{n} \quad (2)$$

where X_{1j} and X_{2j} are responses of two different configurations for the j run, n is the total number of runs and $Z_j = X_{1j} - X_{2j}$. Given this equation, inducing positive correlations between X_{1j} and X_{2j} (considered in the covariate term in the equation) reduces the estimated variance of the difference of a certain metric in a simulation.

Antithetic variates

The antithetic variates (AV) technique operates in a similar way than common random numbers, with the difference that it induces a negative correlation between the replications of the same configuration. With this purpose, the technique synchronizes the random numbers of each pair of replications: if in the first run of the model a process uses a random number U in a given moment, for the next replication the model will use the random number $U - 1$ for the same process at the same moment. Equation 3 shows an unbiased estimator of the variance between the response of different runs

$$Var\left[\overline{X}(n)\right] = \frac{Var(X_j)}{n} = \frac{Var\left(X_j^{(1)}\right) + Var\left(X_j^{(2)}\right) + 2Cov(X_j^{(1)}, X_j^{(2)})}{4n} \quad (3)$$

where $X_j = \frac{(X_j^{(1)} + X_j^{(2)})}{2}$ (that is used to define an unbiased estimator of the variance between runs) and $X_j^{(1)}$, $X_j^{(2)}$ are responses of the model for one pair of replications of the configuration j. Equation 3 shows that inducing negative correlations between the replications of a certain configuration of the simulation model reduces the unbiased estimator of the variance of the results for each different configuration.

Dynamic Runs

This technique operates by defining a criterion for stopping the model given a certain variance in the results. Recommended by Hong and Nelson [8], the use of dynamic runs (DR) implies stopping the evaluation of additional runs when a variance threshold is reached. The latter causes a direct saving on the computational costs of the evaluation of the objective function. To define the threshold Anderson et al. [2] suggest that if the half-width of the confidence interval is 1% of the mean of the response's estimation, there's no need for more runs of the model. This criterion is expressed in Equation 4

$$0{,}01\,\bar{X} \;\geq\; t^{n-1}_{(1-\alpha)/2}\,\frac{s}{\sqrt{n}} \tag{4}$$

where $\bar{X}$ is the mean of the response for n replications.

4 Proposed Framework

Considering the metaheuristics and techniques, a framework is proposed for evaluating and improving the performance of simulation-optimization methods, saving computational costs, and enhancing the results of the optimization. This three-phase proposal is shown in Figure 1.

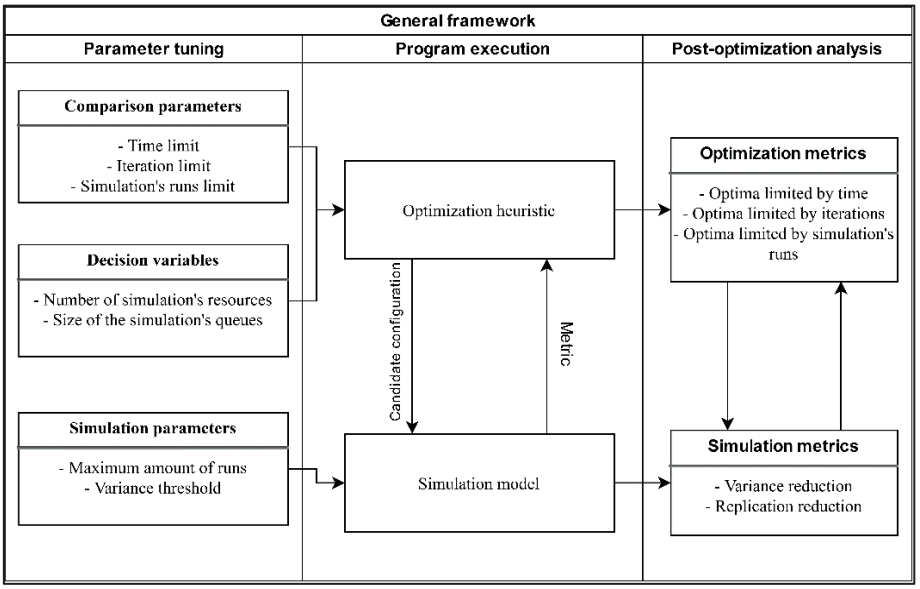

Fig. 1. Proposed framework

The first phase of the proposal is the parameter tuning needed for executing the corresponding simulation and heuristics which are divided into comparison parameters, decision variables, and simulation parameters. The comparison parameters define how to

limit the heuristics operation for adequate execution and subsequent evaluation. Three alternatives are proposed: limitations of time, iterations and simulation runs. The second set of parameters are the decision variables and the corresponding search space. These parameters are given by the optimization problem to solve. The third set of parameters to tune are the simulation-related parameters. These parameters are mainly the maximum amount of runs of the model for each evaluation and the variance threshold. While the former can be defined by sensitivity analysis, the latter can be selected by the suggestion made by Anderson et al. [2] explained in the previous section.

The following phase is the execution of the two systems that interact to solve the optimization problem: the selected heuristic and the simulation model.

Finally, the third phase of the proposal corresponds to a post-optimization analysis to determine the best combination of methods to solve optimization problems and the actual benefit of the techniques implemented. In this phase, two categories of metrics are evaluated: the ones related to the optima reached and the ones related to the simulation model. The first category evaluates the found optimums according to the limitations defined in the parameter tuning phase. The second category measures the variance reduced of the VRT implemented and the reduction of replications achieved by the dynamics runs criterion.

To evaluate the optimum-related metrics several tests and analyses are suggested. These are graphical analysis, parametric and non-parametric difference tests[1] , and a design of experiment (DOE) layout which evaluates the interactions of the methods and techniques implemented. For the simulation metrics, a measurement of the variance reduction for a sample and a quantification of the saved replications are proposed.

5 Numerical Experimentation: preliminary testing

In this section, we present the experimental design and results obtained by preliminary testing of the proposed framework presented in this manuscript. Section 5.1 describes the parameters tuning procedure, and section 5.2 describes the implementation of the simulation models. Section 5.3 presents numerical results.

5.1 Parameters Tuning

For the parameter tuning of the three metaheuristics proposed, a literature review was conducted to define an initial configuration of the parameters to perform preliminary experimentation and gain more insights from a comparative analysis among the three algorithms under the proposed framework. Even though better parameters for each metaheuristic exist, the focus of this work is not on the precise definition of the metaheuristic´s control parameters. To implement these metaheuristics three open-source R libraries were used: optimization for simulated annealing [9], tabuSearch for tabu search [3], and GA for genetic algorithms [20].

[1] Tests like the Student's paired *t*-test and Anova for the parametric case and the Wilcoxon signed-rank test and the Friedman test for the non-parametric scenario.

In terms of the simulated annealing algorithm, it is required that the temperature schedule defines a high temperature for the first iteration and a low temperature for the last iterations. For the temperature schedule, Stander and Silverman [21] report similar performances for logarithmic, exponential, and geometric schedules. For the preliminary testing of SA, a geometric schedule is considered, as indicated by Equation 5

$$\tau_i = f \left(\frac{l}{f}\right)^{\frac{(i-1)}{(T-1)}} \tag{5}$$

where τ_i is the temperature of the iteration i, T the size of the schedule (defined by the number of iterations of the algorithm), f the initial temperature, and l the final temperature. The values of the parameters considered for the experimentation were defined according to some references in the literature such as [7]. For the preliminary experimentation, it was decided to use a final temperature l of 5, a decrease rate of 0.8, and a number of iterations n_{max} of 8. Among these parameters, the most relevant for the implementation of the algorithm was the final temperature l that was chosen evaluating the magnitude of the objective function and the possible differences between configurations. Considering the smoother temperature decrease rate of a geometric schedule and the possible magnitudes of the differences between configurations, a value of 5 allows enhancing the intensification features of the algorithm. The rest of the parameters (f and T) are defined by the number of iterations for the algorithm. Also, to determine how the domain of the function is search, which means how are we going to select the candidate solutions at each iteration, a visiting function is defined based on a uniform distribution with a range given by a factor that depends on the historical ratio of invalid trials (out-bounded values) of solutions [9].

In the case of the genetic algorithms, three parameters must be tuned: the size n of the populations, the crossover and mutation rates. For the selection of the population size, Reeves [17] suggests the relation given by Equation 6

$$P = \left(1 - \left(\frac{1}{2}\right)^{M-1}\right)^{l} \tag{6}$$

where M is the size of the population, l the number of bits (given by the decision variables), and P the chance of every point in the search space being reached. The author suggests a value of at least 99% for P. For the given search space of the simulation models, the number of bits of the variables is 18, resulting in a population size of 12. This population size maximizes the performance of the algorithm while minimizing the computational costs (which increases with bigger populations). For the rest of the genetic algorithm parameters, Grefenstette [6] explores different values concluding that rates of 0.88 for the crossover and a value above 0.05 for the mutation rate are adequate for small-sized populations. Therefore, rates of 0.88 and 0.1 are chosen for these parameters. Finally, a linear ranking-based selection function was implemented with a selection pressure of 0.5 for the preliminary testing as it was the default value that allows to balance the diversification and intensification features of the algorithm.

Finally, for the tabu search, Fouskakis and Draper [4] suggest a tabu list's size of the square root of the number of bits that represent the decision variables. Considering that the amount of bits is 18, an approximation of 4 is made for this value. The last parameter

to decide is the number of neighbors evaluated in each iteration. To select the value of this parameter, a sensibility analysis was conducted executing the algorithm with 5 iterations starting from the same random configuration for each of the possible values (from 1 neighbor to all the 16 possible neighbors). The results showed convergence in the optima found when a number of 8 neighbors are evaluated in each iteration, and this was the value selected for the experiments.

5.2 Simulation Modeling implementation

Similar as in [7,14,19], two discrete-event simulation hypothetical models were developed using R's Simmer library [23] to test the proposed framework. Both generic models share the same number of processes (four in a single-line layout), costs of parameters, and consider the same performance metric (the number of entities that exit the models). The first one, the main model, includes elements to evaluate variance given by complex processes. With this end, the main model was developed with shared resources for the processes, boredom rates for the entities waiting in a queue, and an optional process. The second model, the secondary one, aimed to represent a simpler system but with more variance, deleting all the complex elements of the main model.

The decision variables of the models and the optimization problem are given by the number of resources that each of the four processes has, and the size of the waiting queues for the two first processes, resulting in six decision variables. Considering a bit codification of three bits per decision variable, eight possible values were given for each decision variable from one to eight in the case of the number of resources and two to sixteen in the sizes of both queues. The resulting search space is defined by 262,144 possible configurations. For each model, a maximum number of runs of six was selected. This value was chosen considering a preliminary analysis of the performance of the dynamic runs technique for a sample of 50 random configurations. The results showed that the biggest increment in saved runs was obtained for a maximum number of 6 runs, hence this value was selected to evaluate appropriately this technique and limiting the computational costs of the case study.

5.3 Experimental Results

Simulation's metrics

To evaluate the statistical techniques in the framework two metrics were proposed: the number of replications saved by the dynamic runs technique and the variance reduction caused by CRN and AV.

In the case of the number of replications saved using dynamic runs a sample of 50 different configurations were evaluated in the main simulation model. For a maximum number of replications of six, approximately a 29% reduction of executed runs was obtained. An analysis of different values for the maximum number of replications was conducted showing that the reduction of runs increases using larger maximum replications values for the model. The results are shown in Figure 2.

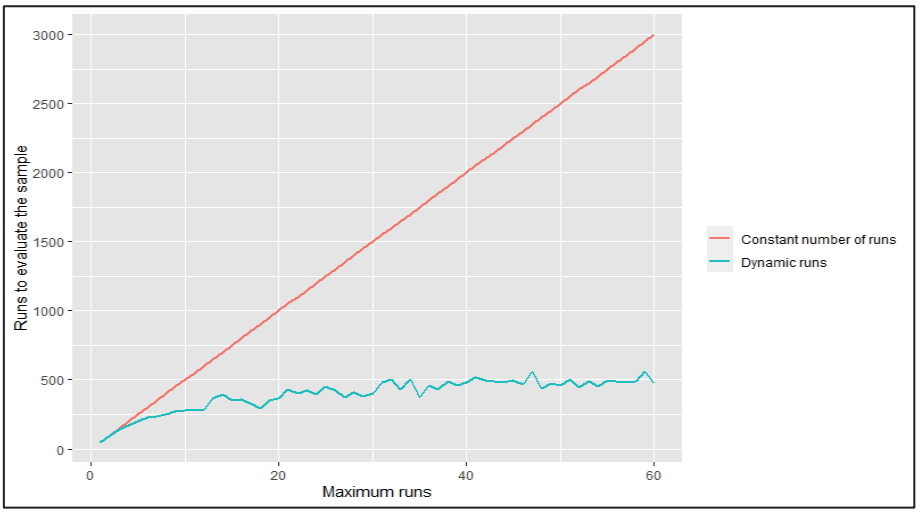

Fig. 2. Executed runs for the chosen sample using dynamic runs

To evaluate the variance reductions techniques, two metrics are defined based on Mawlana and Hammad [15] as described in Equations 7 and 8, which evaluate CRN and AV respectively

$$\Delta \sum_{i,j} S_{i,j}^2 = \frac{\sum_{i,j} S_{i,j\,IR}^2 - \sum_{i,j} S_{i,j\,CRN}^2}{\sum_{i,j} S_{i,j\,IR}^2} \tag{7}$$

$$\Delta \sum_{i} S_{i}^2 = \frac{\sum_{i} S_{i\,IR}^2 - \sum_{i} S_{i\,AV}^2}{\sum_{i,j} S_{i\,IR}^2} \tag{8}$$

where i and j are configurations of the search space, $S_{i,j\,IR}^2$ and $S_{i,j\,CRN}^2$ are the variances of the differences between configurations using independent runs (IR) and CRN respectively, $S_{i\,IR}^2$ and $S_{i\,AV}^2$ are the variances between runs of one configuration using independent runs and AV, respectively.

For the evaluation of the metrics shown in Equation 7 and 8, samples of 45 differences between random configurations and 50 random configurations were tested in the main model. The variance reduction of the differences between configurations caused by CRN was 68.33%. On the other side, the variance reduction of the runs of the configurations obtained using AV was 63.66%.

Optimization metrics

For the preliminary experimentation performed, a total number of 24 iterations of each heuristics were executed, and a limitation of simulation runs was chosen for the analysis. The first approach for the post-optimization phase in the methodology is the graphical analysis. This step is necessary for a complete study of the performance of the techniques and heuristics. Figures 3 and 4 show the results of the found optima by

each heuristic given a certain budget of simulation runs for the main model and the secondary model respectively and the corresponding confidence intervals.

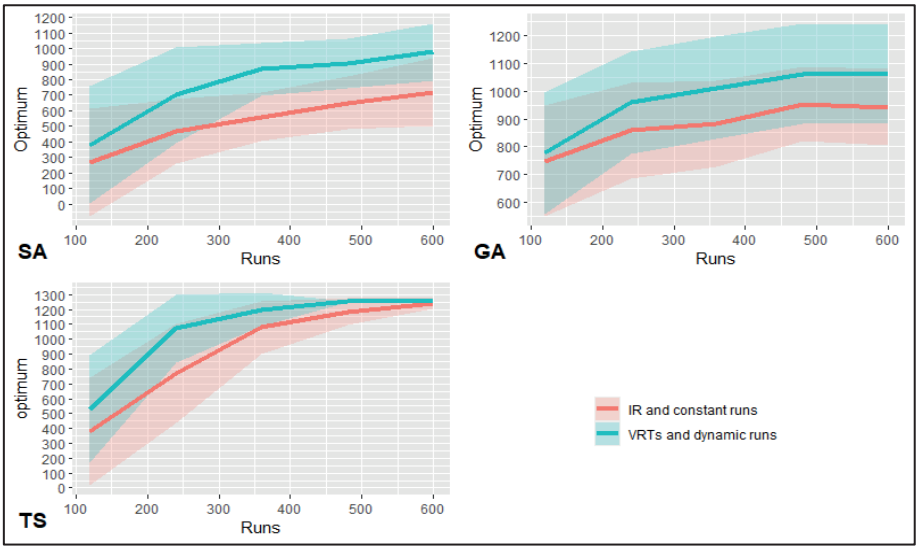

Fig. 3. Reported optimums by each heuristic in the main model

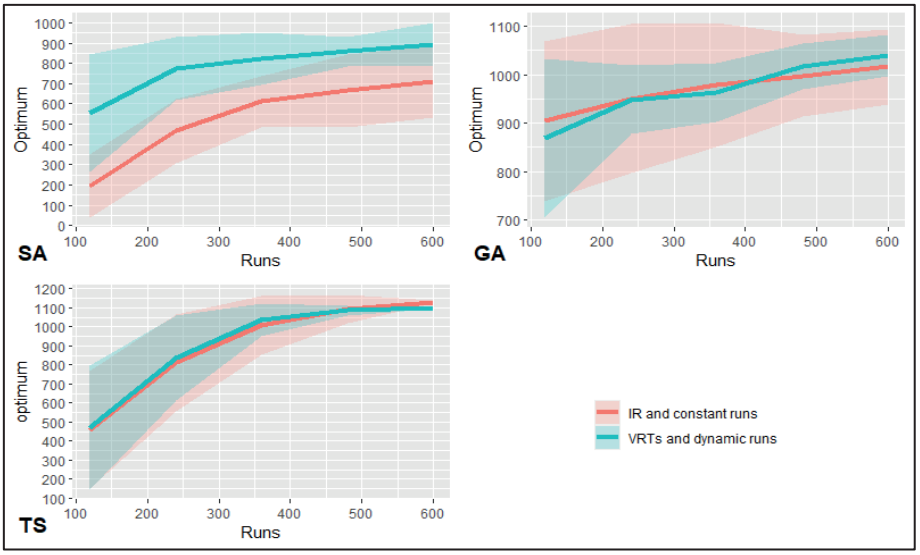

Fig. 4. Reported optimums by each heuristic in the secondary model

Figure 3 and 4 show important improvements on the reported optimums by each heuristic among all the different values of replications, especially for the results of simulated annealing. These results are confirmed by the implemented statistical tests

included in the post-optimization phase. For these tests and the remaining analysis of this section, a fixed budget of 600 and 500 runs is determined for the main and secondary models, considering that none of the metaheuristics have converged to a result with these budgets.

In line with the graphical results obtained, the metaheuristic that achieved the biggest improvements with the statistical techniques was the simulated annealing, that obtained gains of 40.13% and 28.96% in the reported optimums for the main and secondary models respectively. The genetic algorithms also reported important gains from the statistical techniques given by an improvement of 14.93% and 2.05% of the reported optimums for the main and secondary models. Finally, because of the chosen budgets (given by the convergence of the algorithm), the tabu search didn't report significant differences in the performance using the techniques. Nevertheless, the results shown in Figure 3 reports important gains for this metaheuristic with different budgets.

To analyze the effects of the interactions between each of the implemented methods, a mixed-level factorial design of experiments is proposed, where four factors are defined: the heuristic implemented and the use of CRN, AV and DR. Figures 5 and 6 show the results of the interactions that this experimental design obtained for the main model and the secondary model respectively.

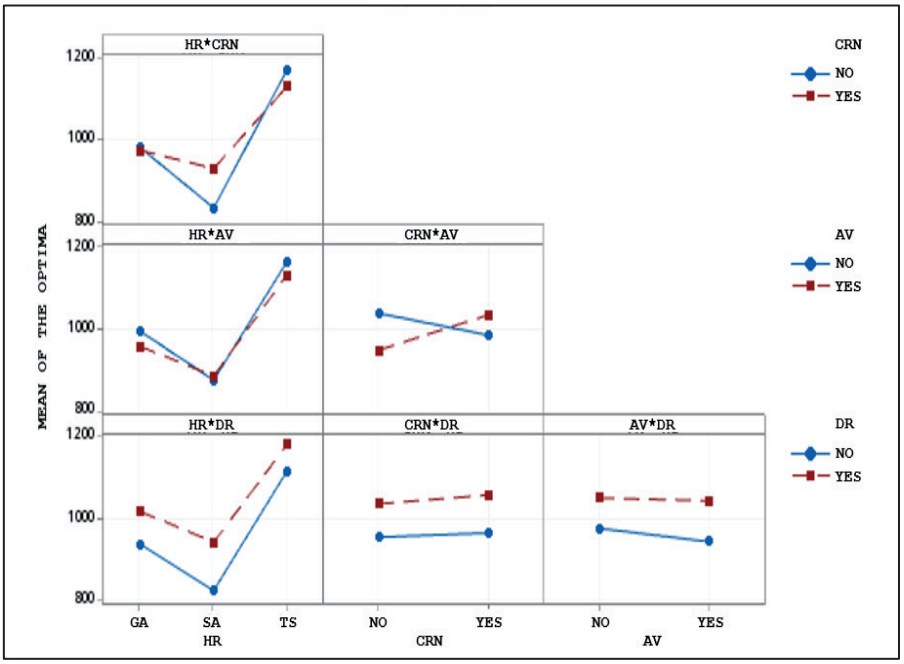

Fig. 5. Interactions of the results of the main model

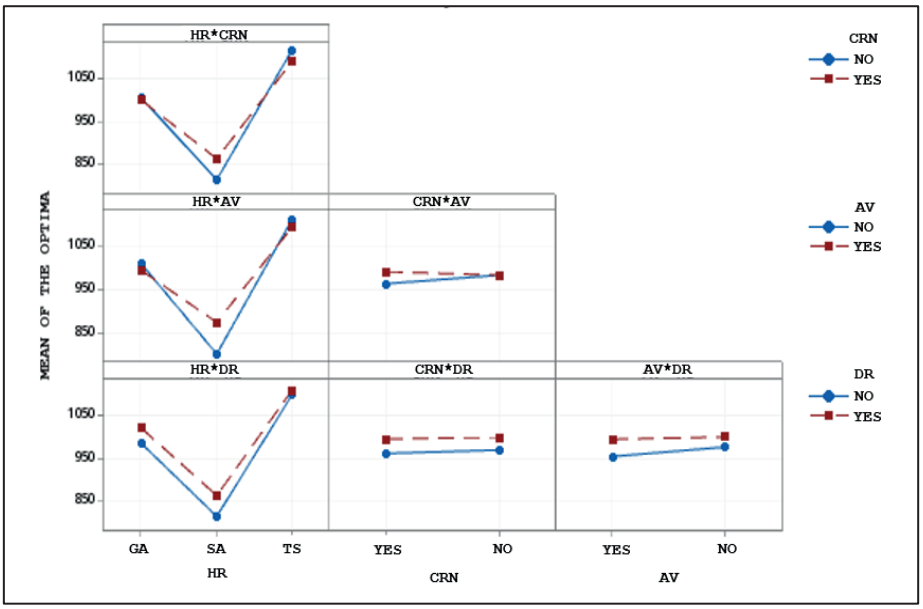

Fig. 6. Interactions of the results of the secondary model

For both models, the significant main effects are the heuristic of choice and the use of dynamic runs. These results show that the heuristic selected is still the most important decision when solving this kind of optimization problem. Also, the use of dynamic runs yields important improvements on the reported optimums.

On the other hand, for the main model, the significant interactions (shown in Figure 5) are CRN*AV, CRN*AV*DR, and HR*CRN*AV. These interactions show inconsistent behavior that can be explained by the unwanted correlations produced by the combination of CRN and AV, as shown by Kleijnen [12]. Also, the significance of the interaction HR*CRN*AV can be explained by the great influence of VRTs on the simulated annealing metaheuristic.

For the secondary model interactions (shown in Figure 6), the effects of HR*CRN*AV, HR*AV, and HR*CRN are significant. The effect of HR*CRN*AV can be explained by the same reason for the results of the main model. On the other hand, the significance of HR*AV and HR*CRN is produced by the benefits that simulated annealing obtain from the VRTs under a scenario with more variance as the secondary model.

6 Conclusions and recommendations for further research

The objective of this work is to propose a framework that analyzes, explores and improves the results of simulation-optimization heuristics using statistical techniques that complement traditional methods. The preliminary experimental results of the

implementation of two simulation models yielded important improvements for all the three heuristics selected.

Accordingly, the dynamic runs resulted the technique that provided better results in terms of the performance of the three algorithms. On the other hand, the obtained results led to the conclusion that a post-optimization analysis is required for the simultaneous application of the two variance reduction techniques. The inconsistent results of the combination of CRN and AV can even harm the search of local optima in some cases. In line with Anderson et al. [2] and Law and Kelton [13], variance reduction techniques are difficult to use due to the lack of understanding of the analysts who implement the simulation-optimization models and always require an effort to at least understand them.

These facts may discourage the use of variance reduction techniques. Nevertheless, due to the positive results obtained in this preliminary testing, independent use of only CRN or only AV may enhance the performance of each heuristic, especially in noise-sensitive heuristics such as simulated annealing, that don't operate with multiple candidate configurations at a time (like genetic algorithms or tabu search).

The work presented in this manuscript provides a first step to define a simulation-optimization framework, contributing to filling a gap that the existing literature [2] fails to address, by exploring the independent effects of each technique and the interactions between them that influence the performance of the different metaheuristics.

For further research, we recommend conducting a complete experimentation, based on the preliminary results obtained that may allow to evaluate different design settings of the metaheuristics, including tunning mechanisms of the control parameters. We also recommend considering hybrid designs of the algorithms due to the advantages that for example tabu search has, and the performance that a low temperature simulated annealing can achieve with variance reduction techniques. Also, the application of the proposed framework in specific decision planning problems that arise from real-world problems is suggested.

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Simulated Annealing Algorithm for In-Plant Milk-Run System

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Abstract. Milk-run, a cyclic material delivering system, aims to increase the efficiency of transportation and supply chain based on lean logistics perspective. There are two kinds of milk-run systems as supplier and in-plant milk-run system in the literature. In-plant milk-run system that has growing appeals with Industry 4.0 concept, is applied to manage the process of delivering materials from warehouse to assembly stations in plants. This system can be implemented using Autonomous Vehicles (AV), which provide automated materials handling. However, a challenging problem arises in determining milk-run routes and periods for each AV, simultaneously. Besides, this problem becomes even harder in the presence of assembly stations with buffer stock constraint and requiring more than one commodity (multi-commodity). Since this problem is quite difficult to handle with exact solution methods, this problem is tackled here by using Simulated Annealing algorithm. To evaluate the performance of the proposed algorithm, we carry out experiments using a range of test problems. The computational results indicate that the suggested algorithm is efficient to obtain both milk-run routes and periods for each AV in reasonable computation times.

Keywords: Autonomous Vehicles, In-Plant Milk-Run System, Buffer Stock Area, Multi-commodity, Simulated Annealing Algorithm.

1 Introduction

Over the past decades, competition among companies around the world has become increasing. To survive in this competition environment, material handling system is one of the most important issue that should be well managed for companies. Some studies have revealed that it can account for 30-75% of the total cost and a well operated material handling system can reduce plant's operating cost by 15-30% [1]. Moreover, efficient material handling system ensures on time delivery, which is a key factor in the implementation of a lean logistics. It is a logistics application in lean manufacturing environment and provides the delivery of the products at the right time to the right place, effectively [2]. The implementation of lean logistics provides some benefits such

as balancing production line, reduction of stock levels and elimination of delays in the logistics process [3].

Lean logistics activities consist of 3 parts such as in-bound, out-bound and in-plant logistics [4]. While in-plant logistics deals with logistics in the factory, in-bound and out-bound logistics deal with obtaining raw materials and delivering goods to the customer, respectively [5]. These three types of logistics affect each other implicitly and one problem in any of them signify that there will be a problem in the others. For this reason, the logistics process should be carried out in a good way at all levels, simultaneously.

There is a correlation between a just in time plan and a good logistics strategy [6]. For in-plant logistics just in time material supply is a vital issue, because early material supply causes inventory holding cost and late material supply causes stopping assembly lines due to the parts shortage [7]. Milk-Run system, cyclic goods taking, is able to reduce these kind of delays in manufacturing especially in assembly lines [8]. Indeed, milk-run system can also be considered as a special kind of Vehicle Routing Problem with Time Windows [9]. Since it is actually a lean logistics method, it is possible to be implemented for all three types of lean logistics. There are two different milk-run systems as supplier milk-run and in-plant milk-run system in the literature [4]. With the supplier milk-run system, goods are collected from external suppliers and delivered to a customer by following a predefined route [10, 11]. On the other hand, in-plant milk-run system helps to deliver materials from warehouse to assembly lines in plants in a cyclic manner. Moreover, implementation of this system to the factory, mass production is made, is appropriate because many different materials should be delivered to the assembly stations at certain periods [12]. Unlike supplier milk-run system, it is not affected by external factors such as weather conditions. Accordingly, schedules of in-plant milk-run system are more reliable and robust [4]. The objective of in-plant milk-run system can be defined as minimizing the total inventory holding and transportation cost to ensure no parts shortage will occur in assembly stations.

In plant Milk-Run systems has some certain advantages listed below [13];

- Improved performance of the supply chain and logistics because of effective transportation,
- Lower inventory and reduced maintenance costs,
- More effective use of buffer stock area,
- More appropriate and reliable delivery times,
- Increased capital turnovers,
- Increased flexibility in supplying the parts,
- Smooth and well-established logistic operations.

Choosing the right material handling equipment is essential to improve facility utilization, increase efficiency of material flow, reduce waste in plant and provide effective utilization of manpower [5, 14]. There is growing interest using automated material handling vehicles especially with the Industry 4.0 concept. In this sense, in-plant milk-

run system can be applied using Autonomous Vehicles (AV). Contrary to Automated Guided Vehicles (AGV), AV navigates autonomously in the environment without any limitations on the paths. Therefore, it is more convenient to use AV in flexible logistics system which should be used in just in time production.

In-plant milk-run system is applied to manage process of in-plant logistics. Operating this system effectively is important not only for minimizing material handling cost, but also for ensuring continuity of production process. Demands of the assembly stations have to be satisfied from warehouse using AV by taking into account paths and time scheduling without causing any parts shortage. Therefore, it is crucial to obtain well designed milk-run routes and periods for each AV. In the meantime, milk-run period affects delivery quantities of the assembly stations and this influences milk-run route construction process because vehicle capacity is fixed [15]. So, the problem of obtaining milk-run period and route should be handled together. In addition, milk-run routes and periods should be determined considering demands of the assembly stations, capacity of buffer stock area, the number of vehicles and their capacities.

This study is set out to explore the design of in-plant milk-run system. Milk-run routes and periods must be obtained simultaneously to operate system, effectively. Although they are common issues, the inherent difficulties make this problem tough. These are the presence of AV capacity, limited buffer stock area and assembly stations requiring multi-commodity goods. Accordingly, related problem can be explained as obtaining milk-run routes and periods for AVs with the minimum total transportation cost to satisfy the demand of assembly stations in a cyclic manner.

Our research aims at developing effective solution method for obtaining milk-run routes and periods simultaneously for AVs in-plant. With this aim in mind, a novel method which is based on Simulated Annealing algorithm has been designed to solve this challenging problem in reasonable computation times. The structure of the generic Simulated Annealing algorithm is enriched by various neighbor search procedures used in probabilistic manner. To evaluate the performance of the proposed method, we carry out experiments using generated test problems. The key contribution of this work is solution representation that provides all information about milk-run routes, periods and it enables exploring the solution space effectively. Another contribution is that proposed approach gets high quality solutions at reasonable computation times even for large-scale problems.

The rest of the papers is organized as follows. The relevant literature is reviewed in Section II. Section III describes the related problem and gives detailed information about the proposed method. Test problems and computational results are presented in Section IV. Finally, Section V concludes the paper and provides future researches.

2 Literature Review

There is an increased attention to in-plant milk-run system area. So, a significant variety of designs of this system is found in the literature. Here we will discuss the literature which is relevant to our approach.

The problem that has arisen in obtaining milk-run routes and periods in-plant has been handled by researchers in different ways. Some researchers suggested exact solution methods, others developed heuristic methods. Besides, good overviews of earlier works in milk-run logistics and in-plant milk-run system is presented by [11] and [12].

First of all, studies proposing the exact solution method has been examined. Akillioglu et al. [16] proposed a mixed integer mathematical model to obtain route and cycle time for in-plant milk-run system. The objectives of this model is to minimize total inventory and distribution costs. The results of the mathematical model are evaluated by using a simulation model. Kilic et al. [5] classified the milk-run distribution system and developed a mathematical model for each case. The objective function of proposed mathematical models is to minimize the number of vehicles and the total travelled distance in-plant milk-run system. The most important finding in this study is that using multiple routed milk-run trains are more advantageous than one routed milk-run trains. Similar work has also been pursued by Kilic and Durmusoglu [17] in which they focus on periodic material delivery in lean production environment. They proposed a mixed integer linear programming model to minimize transportation costs. Volling et al. [18] developed a combined inventory-transportation system with multi-product, multi-vehicle and stochastic demand. They proposed an exact decomposition approach to handle the related problem and reported that substantial gains are achieved by this approach. Emde and Gendreau [19] explored scheduling tow-train with predefined routes to feed parts to automotive assembly lines. They developed a mixed-integer mathematical model to minimize in-process inventory cost. A more efficient implementation for in-plant milk-run system has been proposed relatively recently by Satoglu and Sipahioglu [7]. Because, they proposed two different assignment based mathematical model for just in time material supply system of the assembly lines. One of the models doesn't guarantee obtaining the global optimum solution, but this model performs better performance with regard to computation time. Mao et al. [20] introduced "Milk-run routing problem with progress lane (MRPPL)" to the literature. This problem is about to collecting automobile parts by integrating the progress-lane into the corresponding vehicle routing problem. They proposed a mixed integer linear programming model for small scale problems. Buyukozkan et al. [21] focused on in-plant milk-run system application in white goods industry. To maintain the assembly lines' operations, they proposed a mathematical model for single-vehicle case milk-run system with predetermined periods. Buyukozkan and Satoglu [22] also proposed a mathematical model for multi-vehicle case milk-run system with predetermined cycle times. Sipahioglu and Altin [23] dealt with in-plant milk-run system with predetermined periods. They developed a new mixed integer mathematical model to obtain milk-run routes and periods for AGVs. This

model allows split deliveries for stations and increase vehicle capacity by adding trailers. Besides, the proposed model has less number of constraints comparing the others and quite short computational time to obtain the optimal solution.

Studies proposing the heuristic methods has been reported as follows. Golz et al. [24] explored just in time part supply system with predefined routes to minimize the required number of shuttle drivers. They developed a heuristic solution procedure consisting of two stage. Gyulai et al. [9] proposed an initial solution generation heuristics and a local search method to solve the vehicle routing problem to obtain routes for in-plant milk-run planning problem. Kilic and Durmusoglu [17] tackled periodic material delivery in lean production environment with a predefined route in equal cycle times. They proposed a heuristic method since the optimal solution could not be obtained when scale of the problem gets bigger. Fathi et al. [25] discussed the assembly line part feeding problem with predefined tours. They suggested a modified particle swarm optimization algorithm to solve two sub-problems which are tour scheduling and tow-train loading problems. Emde and Gendreau [19] also offered a decomposition heuristic to solve instances of realistic size in acceptable computation time for scheduling tow-train with predefined routes. Mao et al. [20] also proposed genetic algorithm to obtain trip routes to collect automobile parts within a reasonable computation time for large size instances. Buyukozkan et al. [21] focused on in-plant milk-run system with predetermined period, multi product and limited buffer stock area. They proposed matheuristic algorithm that solve the proposed single vehicle milk-run model iteratively for multi vehicle case. Buyukozkan and Satoglu [22] proposed artificial bee colony algorithm to solve large scale in-plant milk-run instances with predetermined cycle time, multi product, multi vehicle and limited buffer stock area.

It is clear that, previous works are aimed at obtaining milk-run routes and periods for vehicles to minimize total cost of in-plant logistics. It is understood from these studies that the related problem can be extended in terms of the problem size and computation times. On the other hand, a solution approach that enables obtaining milk-run routes and periods simultaneously for large scale problems will contribute to the literature. In this sense, we proposed Simulated Annealing algorithm for in-plant milk-run system with multi commodity, multi vehicle and limited buffer stock area.

3 Problem Definition and Proposed Method

Companies take care not to stop assembly stations due to the parts shortage and make an effort to ensure continuity of production in plant. Therefore, it is vital to satisfy demands of the assembly stations on time. Since different operations are carried out at each assembly stations, the material types and quantities required by the stations may differ from each other. Accordingly, assembly stations must be fed periodically by AVs to minimize total transportation costs. In this feeding process, routes and periods for AVs should be obtained in accordance with the following conditions and assumptions:

- Each route starts and ends at the depot.
- Each AV is operated at most only one route.

- Each station is visited only once.
- AVs are homogenous.
- Each assembly stations have only delivery demands.
- Demands of each station are known but varies with regard to milk-run period.
- Distances between assembly stations are known and used as a distance matrix.
- Unloading time at each station is limited to 0.5 minute.
- Speed of each vehicle is 10 meters per minute.
- There are limited and known buffer stock area for each station.
- Stations require different types of goods.

Taking into account all of these, it is necessary to determine milk-run routes and periods for each AGV in order to operate in-plant milk-run system. However, a challenging problem arises in determining milk-run routes and periods simultaneously. This problem is difficult to handle by exact solution method in reasonable computation times. Therefore, we have developed Simulated Annealing (SA) algorithm.

SA algorithm was proposed by Kirkpatrick et al. [26] and Černý [27] as a single solution based metaheuristic approach. SA is a stochastic neighborhood search method that imitates the physical annealing process where a solid is slowly cooled until the minimum energy state is achieved. Therefore, not only improving solutions are always accepted, but also non-improving (inferior) solutions can be accepted by acceptance probability of the Metropolis criterion. This acceptance probability function is the main mechanism of SA algorithm and prevents getting stuck into local optima [28]. Thus, this algorithm provides obtaining high quality solution in a reasonable computation time. Because of its simplicity and efficiency, SA algorithm has widely been applied to solve most of the combinatorial optimization problems.

In order to apply metaheuristic algorithm effectively, an appropriate solution representation structure should be used. It should be easy to generate new and feasible solutions from a current solution. Proposed solution representation is shown in Figure 1. It consists of positive and zero numbers. Positive numbers represent delivery customers and zero numbers indicate vehicles. So, this solution representation length is related to the number of customers and vehicles.

8	2	5	0	1	9	7	0	6	4	3

Fig. 1. An example of solution representation.

The main advantage of suggested method is the suggested solution representation. This representation provides all information about milk-run routes and periods that are vital to operate in-plant milk-run system, efficiently. Referring to Figure 1, it is clear that there are 9 customers and 3 vehicles. Milk-run routes for each vehicle are as follows; first route is 0-8-2-5-0, second route is 0-1-9-7-0 and third route is 0-6-4-3-0. On the other hand, milk-run periods are calculated taking into account trip time of route and unloading time at each station.

SA algorithm was modified to achieve high quality solutions by using different neighbor search operators. Four different search operators have been used such as swap, insert, 3-change and reverse. These operators have been used probabilistically with regard to the scale of the problem. For small scale problems (number of customer ≤ 45), only swap, insert and 3-change operators have been used with equal probability. On the other hand, for medium (number of customer ϵ [55, 95]) and large scale problems (number of customer ≥ 150), all operators have been used with equal probability. Moreover, the number of iteration has been used as a stopping criteria and geometric cooling schedule has been used in this algorithm.

These neighbor search operators are robust and ensure obtaining milk-run routes and periods in any case. For example, route and period information is obtained from the customer numbers that are among zero values in the neighbor solution obtained by swap operator. On the other hand, if there is no customer number among the zero values, then it is understood that one of the vehicles is not used. So, the presented method is capable of generating feasible neighbor solution at each iteration when capacity of AVs and buffer stock areas is ignored.

Capacity of AVs and buffer stock areas is allowed to be exceeded in order to take advantage of the information about different solutions. A penalty function has been proposed to prevent the capacity to be exceeded in the final obtained solution and it also makes exploring the solution space, extensively. Pseudo code of the developed algorithm is given below.

Pseudo Code of Proposed Simulated Annealing Algorithm

Definitions:

s: solution	$f(s_0)$: objective function value of the initial solution
s_0: initial solution	$f(s')$: objective function value of the neighbor solution
s': neighbor solution	
$f(s_{best})$: objective function value of the best obtained solution	
s_{best}: the best obtained solution	α: cooling rate
T_0: initial temperature	T: current temperature
P: penalty coefficient	e: Excess capacity value

Preliminary Step:

Generation of the initial solution (s0), calculate objective function (f(s0)
$s_{best} := s_0;\ f(s_{best}) := f(s_0);\ s := s_0;\ f(s) := f(s_0)$
Determine the initial temperature and cooling rate
$T := T_0;\ \propto = 0{,}99$
Determine neighbor search operators to be used based on the problem size.
Determine the number of iteration.
Determine stopping criteria for the algorithm.

```
Repeat
     Repeat
          Generate s′ neighbor solution randomly with one
of the swap, insert, 3-change and reverse operators
          Calculate f(s′) with penalty function
          f(s′): = f(s′) + (p ∗ e);
          Δ= f(s′) − f(s);
          If Δ≤ 0;
               Accept neighbor solution (s: = s′);
          Else;
               Generate random number u = (0,1);
               If u < e^(−Δ/T), accept neighbor solution (s: = s′);
          If f(s′) < f(s_best);
               The best obtained solution (s_best: = s′)
     Until (the number of iteration)
     Update temperature T: = T ∗∝
Until (Stopping Criteria Satisfied)
Return the best obtained solution and objective function
value s_best, f(s_best)
```

The success of the algorithm is discussed in following section on generated test problems.

4 Computational Results

Here we evaluate the performance of our approach by using test instances. Firstly, environment features and parameter values of the problem are explained in detail over a small size test instance. Afterwards, this problem was solved for different scenarios and the obtained results are presented. Finally, parameter values used in generating test problems, the proposed algorithm parameters and the obtained results are mentioned.

A visual representation of generated test instance having 15 assembly stations and 1 warehouse is shown in Figure 2. Different types of materials are available in the warehouse and homogenous Autonomous Vehicles operated to transport these materials to assembly stations are ready for use. Besides, vehicle roads in the facility are shown with dashed lines. It is important to note that material transfer is carried out without exceeding vehicle capacities and buffer stock capacities of assembly stations.

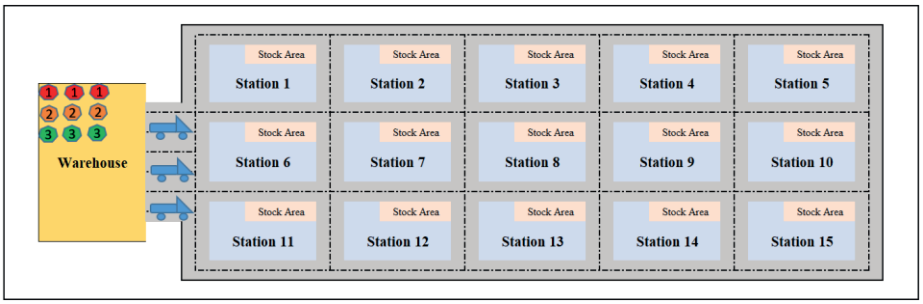

Fig. 2. Representation of facility layout.

There are 10 homogenous AVs available in this instance. Capacity of AVs is expressed on volume based. Therefore, the volumes of the materials to be transported should not be larger than the volume of the vehicle capacity. In addition, there is a fixed usage cost of AVs and unit material handling cost per distance covered. Capacity, fixed usage cost and unit material handling cost of these AVs are denoted in Table 1.

Table 1. Autonomous Vehicle Properties.

Number of AVs	**Capacity of AVs** (cm^3)	**Usage cost of AVs ($)**	**Unit material handling cost** $(\$/meter)$
10	1000	100	2

Assembly stations demand three different types of materials in this instance. Inventory holding cost that will occur if these materials are kept in buffer stock area and volume values of these materials are presented in Table 2. Additionally, the total inventory holding cost for each assembly station is calculated by multiplying half the amount of materials in the buffer stock area by the unit inventory holding cost.

Table 2. Material Properties.

Material Type	**Unit inventory holding cost** $(\$/cm^3)$	**Volume of a box of material** (cm^3)
Material 1	2	5
Material 2	5	10
Material 3	5	2

In this system, the demands of assembly stations must be satisfied on time and these stations must continue to operate by efficient transportation method. However, each assembly stations have a certain number of material demands in different periods based on their material consumption rates. Expressing station requests in different periods with this manner will cause complication. For this reason, 10 minutes' material demands of the assembly stations are calculated based on the original requests and stand-

ardization is provided in the feeding process with this way. Demands of assembly station for 10 minutes and capacity of buffer stock area for each station are shown in Table 3. It can be understood that the 3rd station requests 4 boxes of material-1, 7 boxes of material-2 and 3 boxes of material-3 every 10 minutes. These amounts are known but varies with regard to the obtained milk-run period. To illustrate, if the AV serving 3rd station has a period of 15 minutes, so 3rd station will demand 6 boxes of material-1, 10.5 boxes of material-2 and 4.5 boxes of material-3 every 15 minutes.

Table 3. Assembly Station Properties.

Assembly Station	**Capacity of buffer stock area (cm^3)**	**Demand (box / 10 min.)**		
		Material 1	**Material 2**	**Material 3**
1	750	3	3	2
2	750	9	6	2
3	750	4	7	3
4	750	4	1	2
5	750	3	7	3
6	750	7	8	0
7	750	7	0	2
8	750	4	0	0
9	750	2	1	1
10	750	5	5	1
11	750	3	2	6
12	750	7	3	7
13	750	8	3	7
14	750	4	4	0
15	750	7	0	1

The proposed algorithm was run for the test problem (scenario-1) whose characteristic is given above. In addition, 2 different scenarios have been created since it is worth testing how well the proposed algorithm performs in different conditions. These scenarios were generated by using different capacity values for AVs and buffer stock areas. Capacity of AV and capacity of buffer stock area were determined as 500 (cm^3), 375 (cm^3) in scenario-2 and as 250 (cm^3), 150 (cm^3) in scenario-3. So, it will be observed how the proposed algorithm will handle tight capacity constraints. The proposed SA algorithm has run 5 times for this problem and the best obtained results have denoted in Table 4. The parameters of the algorithm (initial temperature, final temperature, number of iteration at each temperature and cooling rate) were specified as $(T_0, T_f, I, \propto) = (75, 0.1, 100, 0.99)$.

Table 4. Results of the Test Problem.

Scenarios	# of Stations	# of AVs	Routes	Travel Times (min.)	Unloading Times (min.)	Periods (min.)	Total Cost ($)	Computation Times (second)
1	15	3	Route-1 (0-10-12-3-13-15-4-9-0)	17.9	3.5	21.4	1940.5	11.92
			Route-2 (0-2-8-1-0)	14.8	1.5	16.3		
			Route-3 (0-6-11-7-5-14-0)	19	2.5	21.5		
2	15	4	Route-1 (0-1-8-2-9-0)	11.8	2	13.8	2098.6	12.02
			Route-2 (0-5-13-4-15-0)	18.1	2	20.1		
			Route-3 (0-10-6-11-7-0)	13.3	2	15.3		
			Route-4 (0-3-12-14-0)	16.6	1.5	18.1		
3	15	7	Route-1 (0-13-15-0)	13.8	1	14.8	2943	12.04
			Route-2 (0-3-10-0)	11	1	12		
			Route-3 (0-8-2-9-0)	11.8	1.5	13.3		
			Route-4 (0-4-12-0)	17.4	1	18.4		
			Route-5 (0-1-11-7-0)	16.8	1.5	18.3		
			Route-6 (0-5-14-0)	11.9	1	12.9		
			Route-7 (0-6-0)	8.2	0.5	8.7		

Table 4 provides the computational results of the related test problem in terms of 3 scenarios. In order to minimize total transportation costs in each scenario, milk-run routes and periods for AVs were obtained simultaneously. Column 2 and column 3 gives information about the number of assembly stations and the number of AVs operated in each scenario. The milk-run routes obtained for AVs are demonstrated in column 4. In this column, while the warehouse is denoted by 0, the assembly stations are shown by their numbers. The 5th and 6th columns show the travel times and the total unloading times for the relevant route, respectively. In the 7th column, milk-run periods obtained for AVs are specified. Each milk-run period is achieved by summing travel time and unloading time of the relevant route. The obtained total cost values for each scenario are shown in column 8 and the last column contains computation times which are given in seconds.

From Table 4, it can be understood that there are 3 AVs to satisfy demands of 15 assembly stations in cyclic manner for scenario-1. First AV supplies material 10, 12, 3, 13, 15, 4, 9th stations every 21.4 minutes, second AV supplies material 2, 8, 1st stations every 16.3 minutes and third AV supplies material 6, 11, 7, 5, 14th stations every 21.5 minutes. Thus, considering all cost items, the total cost was obtained as 1940.5 for scenario-1.

There are several points to note concerning the computational results. While 3 AVs were used in scenario-1, 4 AVs in scenario-2 and 7 AVs in scenario-3 were used. Besides, when these three scenarios are compared, the minimum total cost value was obtained in scenario-1, on the other hand the maximum total cost value was obtained in

scenario-3. These implications represent the impact of tight capacity constraints. That is to say, as the capacity of AVs and buffer stock areas is decreased, the number of AV needed and the total cost values increase. Moreover, it is observed that the duration of milk-run periods is shortened with tight capacity constraints. In addition, it is seen that there is no significant difference between 3 different scenarios with regard to computation times.

Different scale of test problems was generated to demonstrate the effectiveness of the developed approach. 15 different test problems were generated and classified as small, medium and large scale. All the parameter values of these test problems were expressed in Table 5. Besides, the parameter values used in the SA algorithm are shown in Table 6.

Table 5. Test Problem Parameter Values.

Parameters	**Small scale problems**	**Medium scale problems**	**Large scale problems**
# of AVs	10	15	50
# of Assembly stations	[10, 45]	[55, 95]	[150, 500]
Capacity of AVs (cm^3)	1000	5000	40000
Capacity of buffer stock area (cm^3)	750	1500	10000
Usage cost of AVs ($)	100	300	500
Unit material handling cost ($/meter)	2	3	5
Distance matrix	uniform(5,100)	uniform(5,100)	uniform(5,100)
# of Material types	uniform(2,5)	uniform(5,10)	uniform(10,20)
Material demands of stations (box / 10 min.)	uniform(0,10)	uniform(0,10)	uniform(0,10)
Volume of a box of material (cm^3)	uniform(2,20)	uniform(2,20)	uniform(2,20)
Inventory holding cost ($/$cm^3$)	uniform(1,5)	uniform(1,5)	uniform(1,5)

Table 6. SA Parameter Values.

	Small scale problems	**Medium scale problems**	**Large scale problems**
Initial temperature (T_0)	75	100	200
Final temperature (T_f)	0.1	0.1	0.1
Number of iteration (I)	100	150	200
Cooling rate ($\propto$)	0.99	0.99	0.99

The proposed algorithm was coded in Python 3.7 and run on an Intel Core i5 1.8 GHz PC with 8 GB memory. This algorithm has run 5 times for each test problem and the best obtained computational results have been presented in Table 7.

Table 7. Numerical Results of the Proposed Algorithm on the Test Problems.

Test Problem	**# of Stations**	**# of AVs**	**Total Cost ($)**	**Computation Times (second)**
S-1	10	3	1831	10
S-2	15	3	1940.53	12.5
S-3	25	5	3091.60	12.6
S-4	35	10	5463.46	25.7
S-5	45	9	5583.93	23.5
M-6	55	10	12509.91	84.2
M-7	65	12	15674.95	114.8
M-8	75	12	15729.10	107.4
M-9	85	15	21589.68	160.2
M-10	95	15	26836	181.6
L-11	150	28	64697.27	1043
L-12	200	35	89325.96	1445.9
L-13	300	50	120402.67	1583.7
L-14	400	50	196526.37	2601.9
L-15	500	50	287402.60	3603.2

Numerical results of the different scale instances are summarized in Table 7 in terms of the number of assembly stations, the number of AVs operated, total cost and computation times. The first two columns of Table 7 contain information about test problems, such as instance name and the number of assembly stations. Third column shows the number of AVs used in test problems. Next column indicates the obtained total cost value and the last column includes computation times given in seconds. In these test problems, different milk-run routes and periods for AVs were obtained simultaneously in order to minimize total cost for in-plant milk-run system. So, the demands of the assembly stations have been satisfied by AVs in cyclic manner without violating ca-

pacity constraint for AVs and buffer stock areas. There is a significant positive correlation between problem size and the number of AVs and computation times needed. In other words, as the size of the problem increases, the number of AVs used and the computation times increases. However, even the L-15 problem which includes 500 assembly stations, 50 AVs and 20 different types of materials was solved in about 1 hour by our proposed algorithm. Therefore, it is seen that the proposed algorithm is able to produce good solutions for even large scale problems at reasonable computation times.

5 Conclusions

This study is set out to explore in-plant milk-run system with regard to material feeding process. The main problem encountered here is obtaining milk-run routes and periods simultaneously for AVs with the minimum total cost to satisfy the demand of assembly stations in a cyclic manner. Besides, this problem is quite difficult taking into account capacity of AV, limited buffer stock area and assembly stations demanding different types of materials. Simulated Annealing algorithm has been proposed to solve this challenging problem. Different neighbor search operators and penalty function have been used the structure of the SA algorithm. In addition, a well-designed solution representation, provides all information about milk-run routes and periods as well as it enables exploring the solution space effectively, has been proposed for SA algorithm. Computational experiment has been carried out for a range of the generated test problems. Computational results show that the proposed approach gets different milk-run routes and periods for AVs simultaneously at reasonable computation times even for large-scale problems. The proposed algorithm can handle even the L-15 test problem including 500 assembly stations, 50 AVs and 20 different types of materials in about 1 hour. Thus, it is seen that the proposed algorithm is a successful approach for in-plant milk-run system with multi commodity, multi vehicle and limited buffer stock area.

The key contributions of this work are the solution representation and obtaining high quality results at reasonable computation times. To the best of our knowledge, this is the first study to propose a metaheuristic algorithm for in-plant milk-run system with multi commodity, multi vehicle, limited buffer stock area and not using predetermined route and period.

In future work, it may be useful to study on a metaheuristic approach that allows split deliveries for assembly stations in-plant milk-run system and different metaheuristics can be used.

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Propuesta de un algoritmo híbrido para la solución del problema de ruteo de vehículos periódico integrando frecuencia del servicio variable

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Resumen. El ruteo de vehículos es uno de los problemas más reconocidos de la literatura, su estudio ha tomado relevancia en los últimos años incluyendo diferentes variantes al problema, en este aporte se llevó a cabo la propuesta de un método de solución de dos fases para un problema de ruteo de vehículos teniendo en cuenta la frecuencia del servicio como característica principal y factores restrictivos de capacidad y ventanas de tiempo, a través de un modelo de programación entera mixta en la primera fase de asignación y la metaheurística de optimización por colonia de hormigas para la segunda fase de ruteo, acompañado de procedimientos locales y de enlace entre las fases, la implementación se hizo en el software Xpress Optimizer, finalmente para la verificación se realizaron pruebas con instancias de tamaños diferentes de la literatura que demuestran la aplicabilidad del método propuesto y sus ventajas sobre otros métodos de solución.

Palabras clave: Metaheurísticas, Métodos de dos fases, PVRP.

1 Introducción

Actualmente las organizaciones de toda índole se están enfrentando a un contexto de alta complejidad, globalización y constantes avances tecnológicos, por esta razón la distribución y transporte se han consolidado como procesos fundamentales dentro de las operaciones empresariales, llevar una adecuada gestión de estos procesos representa varias ventajas entre las cuales se encuentran la reducción del costo final de los bienes o servicios entre 10% y 20%, ofrecer un mayor nivel de servicio de acuerdo a los requerimientos de los clientes e incrementar la competitividad de las organizaciones. El ruteo de vehículos es una de las actividades realizadas con mayor frecuencia, sin embargo, para abordar este problema de naturaleza NP- Hard desde la academia, los métodos de solución exactos existentes implican límites de aplicación dependiendo del tamaño de los datos por aumento de la complejidad computacional, mientras que las heurísticas y metaheurísticas permiten obtener buenas soluciones a costos computacionales aceptables y permitir un manejo de mayor cantidad de datos.

2 Metodología y estado del arte

Para dar solución al problema planteado se realizó la construcción del estado del arte, enfocado al estudio de las diferentes variantes del problema y sus métodos de solución se evidencia la importancia de las heurísticas y metaheurísticas poblacionales, así como la necesidad de orientar el estudio del problema incluyendo la periodicidad como generalización del problema de ruteo de vehículos, se destacan los aportes de [1], [2], [3], [4] y [5]. Posteriormente se realizó un análisis de los métodos de solución heurísticos y metaheurísticos, correspondientes a la optimización por colonia de hormigas y heurísticas locales enfocadas al cumplimiento de los factores restrictivos, las cuales fueron implementadas a través del desarrollo de un algoritmo en el software utilizado. Se tuvieron en cuenta medidas de desempeño para determinar la eficiencia del modelo a través del análisis con instancias reconocidas de la literatura realizando pruebas comparativas con un método de iterativo de dos fases [6] el cual aplica métodos exactos a cada una de las fases para abordar el problema de ruteo de vehículos descrito anteriormente.

3 Algoritmo propuesto

El algoritmo desarrollado comprende dos fases, las cuales son ejecutadas de forma iterativa y enlazadas con dos criterios, ilustradas en la **Fig. 1** y estas son:

3.1 Fase de asignación

La fase número uno corresponde a un modelo de asignación, se utilizan técnicas de optimización a través de programación entera mixta para resolver una programación de visitas requeridas a cada uno de los clientes durante un horizonte de planeación definido, donde se busca reducir el costo de visita total, teniendo en cuenta aspectos como la demanda, la asignación de clientes a cada periodo del horizonte según la frecuencia mínima definida y las unidades faltantes o en exceso, estas últimas si así se requiere pueden ser asignadas a un día ficticio; si existe factibilidad, este modelo proporciona la información de entrada de la fase número dos, particularmente es exportada la información relacionada con los clientes asignados para cada uno de los días.

3.2 Fase de ruteo

Es comprendido un procedimiento de clustering utilizando el algoritmo de K-means modificado sobre la inicialización para facilitar la adecuación de los datos previa la entrada al ruteo, el cual recibe como información de entrada las coordenadas y ventanas de tiempo de cada cliente así como los clientes agrupados con la flota de vehículos disponible, posteriormente se realiza la ordenación respecto a las ventanas de tiempo de apertura de los clientes conformados en cada clúster; el algoritmo de ruteo funciona iterativamente dentro del horizonte de planeación (HP), la ruta es formada a través de etapas con procedimientos inspirados en el comportamiento de las hormigas dentro de una colonia, teniendo en cuenta la aleatoriedad y las heurísticas locales donde en forma

conjunta determinan los valores de probabilidad por arco con el propósito de cumplir con cada una de las ventanas de tiempo, teniendo como resultado la obtención de la mejor ruta según los factores restrictivos, una vez es construida la mejor ruta por hormiga e iteración, se evalúa la factibilidad, en caso de que exista infactibilidad durante alguno de los días del horizonte de planeación será ejecutado el criterio de salida y en caso de que esto ocurra en el día ficticio es ejecutado el criterio del inventario final.

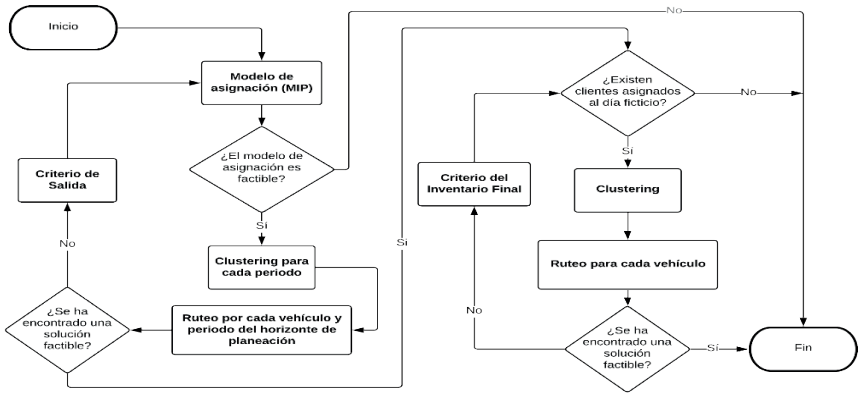

Fig. 1. Diagrama de flujo del método iterativo de dos fases propuesto. Fuente: Autores

3.3 Criterios de salida y de inventario final

Estos procedimientos conectan las fases, identificando los clientes que puedan influir en la infactibilidad de la ruta de algún vehículo durante un periodo donde no se encontró una solución factible, se penaliza el costo de visita del cliente identificado como problemático con el objetivo de que no sea asignado al día donde existió infactibilidad para el caso del criterio de salida, el segundo caso se ejecuta cuando existe una asignación sobre un periodo ficticio adicional al horizonte de planeación y este sea infactible.

4 Análisis de resultados

Se realizó una experimentación entorno a los parámetros del modelo de colonia de hormigas con ventanas de tiempo, determinando la combinación a utilizar dentro del modelo. Los valores a seleccionar de cada parámetro se basan en un diseño de experimentos realizado por [7], se presentan conjuntos de parámetros sobre los cuales se dan dieciséis (16) combinaciones para cada parámetro, ejecutando cinco (5) corridas para cada combinación. Se tuvieron en cuenta dos versiones del modelo propuesto, que se diferencian en el método de inicialización del algoritmo de clusterización, con esto se realizaron un total de 1120 pruebas. La verificación del modelo consta de un análisis con las instancias de Solomon (1987), con conjuntos de 25, 50 y 100 clientes, para el primer tamaño se obtuvo que un 60% de las instancias alcanzó la solución dada por el modelo base de comparación de [6], mientras que en los demás conjuntos de clientes se encuen-

tra que el 70% de las instancias alcanza una solución factible, condicionada a la formación de los clústeres, también se encuentra que se presenta un aumento del tiempo computacional relacionado con el aumento del número de hormigas e iteraciones para garantizar la convergencia del método a una solución factible tras aumentar el tamaño de clientes por visitar.

5 Conclusiones

Dentro de los hallazgos del modelo se aprecia el cumplimiento satisfactorio del algoritmo para dar solución al problema planteado utilizando heurísticas y metaheurísticas y la ventaja que representa para resolver problemas tipo NP-Hard, es notable que el cumplimiento de los factores restrictivos se da por el uso de heurísticas locales y procedimientos de mejora. Se identificó que la aplicación de un algoritmo de clusterización más robusto incrementaría el desempeño del algoritmo en términos de ocurrencia a una solución factible, adicionalmente, criterios que identifiquen diferentes condiciones de infactibilidad existentes dentro del este tipo de problemas. Finalmente es destacable que este tipo de algoritmos representan una complejidad computacional inferior a la obtenida por los modelos de optimización para abordar el problema de ruteo de vehículos y sus posibles variantes, por tanto la cantidad de clientes a considerar está sujeta a la disponibilidad de una licencia o software que soporte el volumen de datos.

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Un algoritmo de Búsqueda Tabú para el problema de Ruteo de Vehículo Milk Run con ventanas de tiempo (VRPMRTW)

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Resumen.
La logística de aprovisionamiento es un factor clave para las organizaciones, esta comprende políticas de compra, gestión de transporte y distribución, diseño de almacenes, gestión de inventarios, entre otras. Cuando los miembros de una cadena de suministro realizan esfuerzos de cooperación con un objetivo en común, la logística Milk Run ofrece una alternativa para manejar el suministro de las materias primas/insumos para esto es necesario establecer una buena programación de las rutas que permitan mejorar la eficiencia en términos de costos y utilización del vehículo sujeto a los horarios establecidos por los proveedores. Esto se puede modelar mediante el problema de ruteo de vehículos Milk Run con ventanas de tiempo. Este problema es de tipo NP-Hard ya que al aumentar el número de pedidos a recoger y estar sujeto a las ventanas de tiempo aumenta la complejidad computacional, por tal razón es necesario el desarrollo de Metaheurísticas para su solución. En la presente investigación se propone un Algoritmo de Búsqueda Tabú. Se adaptaron instancias de la literatura logrando buenos resultados.

Keywords: Búsqueda Tabú, Logística Milk Run, Ruteo de vehículo, Ventana de tiempo.

1 Introducción

Si no se maneja bien la logística de entrada de una fábrica puede causar muchos desperdicios, como tiempo de espera y costos excesivos. Tiempo de espera por falta de materia prima. Costos excesivos, en términos de mantenimiento de inventario por poseer altos niveles de inventarios de materiales y en costos de transporte, por una deficiente asignación de los vehículos y las rutas generadas, estos costos de transporte representan una parte significativa (a menudo entre un tercio y dos tercios) del costo logístico en varias industrias [1]. Por ejemplo, en Colombia el costo de transporte representa entre el 46.2% de los costos logísticos en el sector industrial [2]

Así mismo, puede generar interrupciones en la línea de producción o pérdida de materia prima debido a mayor tiempo de transporte y almacenamiento desde los proveedores al fabricante.

Una alternativa para sincronizar los procesos de transporte y adquisición de materia primas/materiales con el proceso de producción del fabricante ha sido implementar la logística Milk Run que se fundamenta en los principios de producción ajustada. La idea es definir rutas estándar, que se repiten de forma regular (por ejemplo, diariamente o dos veces por semana) para un ciclo de planificación definido (por ejemplo, 3 semanas). Cada ruta estándar consolida las cantidades de reabastecimiento de un grupo de proveedores en una región geográficamente concentrada y define un programa de recolección periódico para cada proveedor [3].

Una cuestión fundamental en el estudio de la logística Milk Run es la definición de la ruta estándar. Dado que el modelo de decisión de ruta se vuelve complejo al aumentar el número de proveedores, tipo de vehículos y la capacidad limitada de los mismos traerá una mayor cantidad de variables de decisión.

Para enfrentar este desafío se ha abordado esta situación mediante el problema de ruteo de vehículos (VRP) en dos variantes: el primero, problema de ruteo de vehículos Milk Run (MRVRP) y el segundo, el problema de ruteo de vehículos Milk Run con ventanas de tiempo (MRVRPTW). La diferencia radica en la inclusión de la disponibilidad horaria de los proveedores para poder cumplir con el plan de producción del fabricante. Estos problemas son de naturaleza Np-Hard, por tal motivo han implementado diferentes metaheurísticas para su solución tales como Algoritmo Genético (GA), Algoritmo de Colonia de Hormigas (ACO) o Algoritmo de ahorros de Clark y Wright.

Sin embargo, no se ha investigado en el desarrollo de un algoritmo de Búsqueda Tabú que utilice la heurística del barrido para obtener la solución inicial. Entonces con el fin de proponer una alternativa de solución diferente a las encontradas en la literatura, se propone un Algoritmo de Búsqueda Tabú para dar solución al problema de ruteo de vehículos Milk Run con ventanas de tiempo (MRVRPTW) cuyo objetivo es minimizar costos.

Se utilizaron instancias sintéticas entonces se recomienda evaluarlos con datos reales. Esta investigación contribuye a soportar una de las principales decisiones del diseño Milk Run, la cual es el ruteo de los vehículos porque si existe una planificación adecuada del ruteo de vehículo contribuye a la eficiencia de la operación logística. Adicionalmente, aporta en mejorar la calidad del diseño de las rutas al reducir el tiempo computacional mediante un método alternativo como lo es el Algoritmo de Búsqueda Tabú.

El algoritmo desarrollado se puede implementar en el área de la logística de entrada de cadenas de suministro sincronizadas dado que se necesita una estrecha relación entre proveedores y fabricante. Los proveedores deben ser de alto valor económico para el fabricante y así mismo que los proveedores sean cercanos entre sí. Dentro de las características del fabricante se resalta que aplica una producción lean y necesite suministro de lotes pequeños con alta frecuencia. El resto del artículo está organizado de la siguiente manera: Sección 2 se presentan los antecedentes presenta la formulación del problema con los antecedentes. Sección 3 la definición del problema, el modelo

matemático y el diseño del Algoritmo de Búsqueda Tabú. Los resultados y su respectivo análisis en la Sección 5 , y finalmente, se presentan las conclusiones.

2 Revisión de Literatura

Mediante la revisión se identificó que el concepto Milk Run es utilizado para describir diferentes situaciones en las cuales ciertas características son más enfatizadas que otras. Las características a las que se hace alusión son las siguientes (1) Milk Runs son rutas fijas con recogidas fijas y franjas horarias de entrega (y volúmenes fijos) los cuales son ejecutados de acuerdo con un ciclo fijo. (2) En Milk Run, LTL de más de un proveedor son consolidados para poder aumentar la frecuencia de envío individual en comparación a ejecutar el transporte directo para cada uno de ellos. (3) Milk Runs son recorridos redondos en los que se intercambian contenedores retornables llenos y vacíos en una proporción de 1: 1. [aclarar bien esto]. (4) Milk runs son planeados por el destinatario [4] .

El problema del diseño Milk Run implica tres subproblemas: El primero, la asignación del concepto del transporte. Segundo, asignación de la frecuencia de reposición y tercero, la decisión del ciclo de programación del ciclo Milk Run. En la línea con el problema integrado [5], [1], [4]. Cuando un conjunto de proveedores decide utilizar el sistema de transporte Milk Run queda por abordar el segundo y tercer subproblema [3], [6], [7], [8], [9], [10]. Respecto al tercer subproblema, cuando se asume que el primer y segundo subproblema están resueltos, es decir, ya están asignados los proveedores al concepto de transporte Milk run y la decisión de frecuencia, cada cuanto se van a despachar los envíos. En este subproblema se necesita definir la secuencia de visitas de cada vehículo considerando la demanda, capacidad del vehículo y/o las restricciones de ventana de tiempo. En el contexto de la logística Milk Run tanto para la logística de entrada como la de salida se distinguen dos problemas principales, el primero es el problema de ruteo de vehículos Milk Run (MRVRP) y el segundo, el problema de ruteo de vehículos Milk Run con ventanas de tiempo (MRVRPTW).

El problema MRVRP ha sido abordado mediante metaheurísticas como Algoritmo Genético (GA), Algoritmo de Colonia de Hormigas (ACO) o Algoritmo de ahorros de Clark y Wright. En [11] propusieron un modelo matemático para el problema ruteo Milk-run con el fin de adaptarlo a las condiciones de un caso de estudio de la industria automotriz. El objetivo era reducir simultáneamente los costos de transporte e inventario abordando tres asuntos: utilizar diferentes proveedores para algunas piezas en particular, determinar la hora exacta en la que un proveedor enviaría las piezas y que un camión pueda trabajar en diferentes rutas en varios horarios. Resuelven el problema mediante el Algoritmo Genético y lo comparan con la estrategia actual obteniendo ahorros en el costo total. Un año más tarde [12] resuelven el problema anterior mediante optimización robusta. [13] propusieron un Algoritmo de Colonia de Hormigas (ACO) con mutación para el problema MRVRP con el objetivo de minimizar el tiempo de finalización más rápido, es decir, el tiempo de finalización de toda la tarea de

distribución es el tiempo de finalización del último vehículo, este lo aplicaron en el contexto de la logística de salida. En el área de la logística de distribución express [14] introdujeron el concepto Milk Run a la logística de distribución. Su objetivo fue minimizar la distancia transportada y los costos de transporte factores Utilizaron un Algoritmo de ahorros de Clark y Wright para resolver el problema. Aplicaron el modelo en una empresa privada de entrega urgente en China. De acuerdo con los resultados reducen el número de vehículos utilizados, la distancia total recorrida, mejoran el factor de carga del vehículo, todo lo anterior contribuye a disminuir el costo logístico.

Por otro lado, con la necesidad de incluir las ventanas de tiempo al contexto de la logística Milk Run varios autores han propuesto diferentes métodos para resolver el problema MRVRPTW tales como: Algoritmo de ahorros de Clark y Wright que combina una solución de dos rutas diferentes para formar una nueva ruta donde se validen los ahorros, Algoritmo de Dijkstra; metaheurísticas basadas en población como Algoritmo de Optimización por Enjambre de partículas (PSO), Algoritmo Genético (GA). [15] propusieron el modelo matemático para el problema MRVRPTW y lo abordaron mediante un Algoritmo de Optimización por enjambre de partículas (PSO).

En [16]proponen un sistema de ruteo de logística Milk Run justo a tiempo basado en el internet de las cosas. El sistema comprende dos subsistemas, es decir, el subsistema de ejecución y el subsistema de decisión. El primero captura las dinámicas del proceso de ejecución de la logística Milk Run y el segundo se encarga de la planificación de rutas iterativa en tiempo real basado en lo que le suministra el subsistema de ejecución, puede haber corrección de cantidad, ruta y vehículo. El modelo matemático de ruta tiene como función objetivo disminuir el costo fijo del vehículo, costo de viaje, una penalización por violar la restricción de carga del vehículo y la cuarta por violar las ventanas de tiempo duras. Diseñan un Algoritmo Genético mejorado y prueban la efectividad del ejemplo mediante un ejemplo de prueba.

[17] plantean una herramienta para la planeación y optimización de la logística Milk Run en el campo de los electrodomésticos. La planificación consiste en dos problemas, el problema de asignación que trata sobre la asignación de los proveedores a los recorridos y el problema de secuencia o enrutamiento para encontrar la secuencia óptima de clientes dentro de un recorrido determinado. En esta investigación dividieron los clientes en dos clústeres de acuerdo con la ubicación geográfica, lo aplicaron en un caso de estudio encontrando una disminución del 11.5% en costos de transporte comparado al enfoque sin aplicar Milk Run.

[18] analizan un caso de estudio en China, determinan los proveedores de transporte directo según la capacidad y para los demás proveedores adoptan el método de mayor frecuencia y lotes pequeños para recoger realizando la circulación, esta situación la modelan mediante el MRVRPTW. El objetivo es minimizar la distancia total recorrida. Diseñaron el Algoritmo de Clark y Wright. Seleccionaron al azar 15 proveedores del área de Shanghái para resolver la mejor ruta. Basados en los resultados mejora la eficiencia del vehículo, reduce el costo logístico y al mismo tiempo, el proveedor logístico y los proveedores logran una situación de beneficio mutuo.

[19] proponen un nuevo modelo matemático para el problema de programación y ruteo Milk Run considerando regulaciones presentes en Estados Unidos como el

máximo permitido de viajes y horas de trabajo. Lo resuelven mediante un Algoritmo Genético y lo aplican a un caso de 11 proveedores.

[20] involucran proveedores de primer y segundo nivel en el modelo logístico Milk Run con el objetivo de disminuir costos sujetos a una restricción de distancia máxima para el recorrido del vehículo y empleó un Algoritmo Genético para su solución. [21] abordaron el problema VRPTW con entrega Milk Run para la entrega de productos frescos y proponen el siguiente enfoque de solución: en primer lugar, obtienen la solución inicial factible con la ruta más corta mediante el Algoritmo de Dijkstra; en segundo lugar, mejoran la solución agregando las restricciones de capacidad de vehículos homogéneos y las ventanas de tiempo. El objetivo es minimizar el costo de la distancia visitada.

Desde el enfoque práctico la logística Milk Run se ha aplicado tanto para la logística de entrada como la logística de salida. En la logística de entrada principalmente en la industria automotriz para el suministro de auto partes en países como China [15], Tailandia [22], Portugal y China [23] , Indonesia [24], Vietnam [25]; en la industria de semiconductores [26]; electrodomésticos [17]. En la logística de distribución en la industria Express en China [14] porque el tiempo y costo son factores competitivos en esta industria, así mismo en la distribución de productos frescos como frutas y vegetales donde la reducción del costo y eficiencia en la utilización del vehículo es de especial interés [21].

3 Método

En esta sección, se presenta la descripción del problema, notación, supuestos y el modelo matemático propuesto por [15] base para la formulación del Algoritmo de Búsqueda Tabú.

3.1 Definición del problema

Se considera una cadena de suministro entre una fábrica y sus proveedores, la fábrica es la que genera la demanda y los proveedores de insumos/materiales están en el lado de la oferta. Esta cadena de suministro ha acordado trabajar bajo el concepto de transporte Milk Run, es decir, recogida y entrega de material en ciclos cerrados y repetitivos. Adicional a ellos se considera la existencia de un proveedor de logística de terceros (3PL). Este proveedor dispone de varios vehículos con la misma capacidad y es el responsable de organizar las rutas de tal manera que el número de vehículos sea mínimo y el costo total de transporte sea menor. Los proveedores solo están disponibles para entregar la mercancía en un horario específico.

El problema se rige bajo los siguientes supuestos:

(1) La demanda de cada proveedor, la distribución espacial de los proveedores y la capacidad de los vehículos del 3PL son conocidas y son iguales.
(2) Cada proveedor debe tener un solo vehículo para recoger los insumos/materiales, y existe una ventana de tiempo para atenderlo. Las ventanas

de tiempo son suaves, es decir, se permite violar las restricciones de las ventanas de tiempo, pero esto implica una penalización económica por incumplimiento que afecta la función de costo.

(3) La capacidad del 3PL es suficiente para cumplir con los requisitos.
(4) Se considera que la mercancía se transporte en pallets estandarizados.
(5) La velocidad media de un vehículo es constante y el tiempo medio de servicio en cada proveedor es igual.
(6) La matriz de distancia es simétrica.

3.2 Modelo matemático

Índices

i: nodo inicial i=1, 2,…, n (i=0 es para el comprador fábrica)
j: nodo final j=1, 2,…, n
k: vehículo k=1, 2,…, m

Parámetros

m: número total de vehículos
n: número total de proveedores
α: Costo de transporte por unidad de distancia
d_{ij}: Distancia entre el nodo i y el nodo j
v: Velocidad del camión
$\boldsymbol{\lambda}$: Costo por llegar antes de la ventana de tiempo.
μ: Costo por llegar después de la ventana de tiempo
V: Volumen máximo del camión
Q: Carga máxima del camión

q_i: Carga del nodo i.
u_i: Volumen demandado por el nodo i
t_{ij}: Tiempo de recorrido entre el nodo i y el nodo j
a_i: Tiempo más temprano para llegar al nodo i.
T_i : Tiempo de carga en el que el vehículo recibe las mercancías del proveedor i.
b_i: Tiempo máximo de llegada al nodo i.
s_i: Tiempo de llegada al nodo i
M: Número entero muy grande

Variables

$$x_{ijk} \begin{cases} 1, \text{si el vehículo k viaja del nodo i al nodo j} \\ 0, \text{lo contrario} \end{cases}$$

$$y_{ik} \begin{cases} 1, \text{si el vehículo k recoge en el punto i} \\ 0, \text{lo contrario} \end{cases}$$

Función Objetivo:

$$Min\ z = \sum_{i=0}^{n}\sum_{j=0}^{n}\sum_{k=1}^{m} C_{ij}x_{ijk} + \lambda\sum_{i=1}^{n} Max(a_i - s_i, 0) + \mu\sum_{i=1}^{n} Max(s_i - b_i, 0) \quad (1)$$

Restricciones

$$\sum_{i=0}^{n} q_i y_{ik} \leq Q \qquad k = 1, 2, \ldots, m \quad (2)$$

$$\sum_{i=0}^{n} u_i y_{ik} \leq V \qquad k = 1, 2, \ldots, m \quad (3)$$

$$\sum_{k=1}^{m} y_{ki} = 1 \qquad i = 1, 2, \ldots, n \quad (4)$$

$$\sum_{i=0}^{n} x_{ijk} = y_{jk} \qquad j = 0,1, 2, \ldots, n, k = 1, 2, \ldots, m \quad (5)$$

$$\sum_{j=0}^{n} x_{ijk} = y_{ik} \qquad i = 0,1, 2, \ldots, n, k = 1, 2, \ldots, m \quad (6)$$

$$x_{ijk} \in \{0,1\} \qquad i, j = 0,1, 2, \ldots, n, k = 1, 2, \ldots, m \quad (7)$$

$$y_{ki} \in \{0,1\} \qquad i, j = 0,1, 2, \ldots, n, k = 1, 2, \ldots, m \quad (8)$$

La función objetivo es minimizar el costo total. La primera parte de la función objetivo indica el **costo total por distancia recorrida, $C_{ij}=\alpha d_{ij}$**. La segunda y tercera parte son los costos de penalización por llegar antes o después de la ventana de tiempo respectivamente. Las ecuaciones (2) y (3) exigen que se deben cumplir las restricciones de capacidad en términos de carga y volumen; la ecuación (4) indica que cada proveedor solo puede ser tomado por un vehículo, la ecuación (5) y (6) indica que cada proveedor tiene el vehículo para recoger y solo se puede visitar una vez.

3.3 Algoritmo de Búsqueda Tabú

Se propone un Algoritmo de Búsqueda Tabú donde se utiliza la heurística del barrido para obtener la solución inicial. Búsqueda Tabú es un algoritmo de búsqueda local, se distingue de otros métodos de búsqueda local por el uso de memoria denominada Tabú donde almacenan las soluciones exploradas recientemente. El tiempo que un atributo permanece Tabú se llama tenencia y el estado Tabúes puede anularse si se cumplen ciertas condiciones. Esto se llama criterio de aspiración y ocurre, por ejemplo, cuando

una solución tabú es mejor que cualquier solución vista anteriormente. [Mejorar esta explicación]

La heurística del barrido tiene como objetivo crear clústeres de proveedores realizando un barrido de estos que permitan agrupar los proveedores más cercanos entre sí hasta incluir la mayor cantidad de proveedores posibles dentro de la ruta, para luego desarrollar la secuencia de las paradas dentro de las rutas.

3.3.1 Representación de la solución

Se utiliza un método de arreglo común para representar la solución tanto proveedores como fábrica, por ejemplo, existe 15 proveedores y 5 tipos de vehículos. "0-12-4-2-13-0-15-14-5-0-10-11-7-6-0-1-9-3-0-8-0", es la ruta inicial la cual consiste en cinco sub-líneas, "0-12-4-2-13-0", "0-15-14-5-0","0-10-11-7-6-0","0-1-9-3-0" y "0-8-0".

La dimensión del vector, D está relacionado con el número de vehículos K y los puntos, siendo D=K+L-1.

3.3.2 Generación del vector inicial o de la solución inicial

El vector inicial se genera a partir de una modificación al método del barrido, pues este empieza en la fábrica (nodo cero), luego busca el más próximo a este, analizando la carga, posteriormente se dirige al nodo más cercano de este último con su respectivo análisis de carga y se devuelve a la fábrica cuando no pueda captar más carga. La modificación busca que la ruta esté lo más cerca a la hora de llegada de cada nodo, por lo cual no se elige el más cercano, sino el que genere menos tiempo de perdida.

El vector inicial se genera a partir del método del barrido, la ruta comienza en la fábrica (nodo cero), luego busca el proveedor más cercano al nodo cero, este sería N1, siendo este el primero que visita el camión. Luego se procede a determinar el vector T_D mediante la ecuación (9), donde T es el tiempo que lleva el camión hasta la hora de salida del nodo anterior.

$$\mathrm{T\_D} = \left(\frac{\mathrm{DIS}(N1,:)}{\mathrm{VP}}\right) + \mathrm{T} \tag{9}$$

Luego de determinar el T_D de la ecuación 11, se procede a restarlo con el vector HLL, generando un nuevo vector llamado T_1, luego se halla la posición del escalar más cercano a cero en el vector T_1, obteniendo el proveedor N2, siendo este el nodo siguiente a visitar.

Una vez determinado el segundo proveedor, se analiza la carga que está llevando el camión en (N2), y si esta es menor a la carga máxima permitida (CG) se procede a repetir el proceso mencionado en el párrafo anterior.

Cuando CG llega a ser mayor en el nodo Nn, el vector inicial (VI) se escribe de la siguiente manera: 0-NI-N2-***-$N_{(n-1)}$-0-Nn, luego se anexa un cero al final para que el último camión pueda retornar a la fábrica. Los nodos visitados van siendo eliminados en la matriz distancia, ventana de tiempo y vector carga para evitar que se llegue a

repetir en la fase del vector inicial. El pseudocódigo correspondiente a la generación del vector inicial se muestra en la Figura 1.

Algoritmo: Vector inicial
Entrada: Matriz distancias (DIS), parte inferior de la ventana de tiempo (HLL), parte superior de la ventana de tiempo (HS), vector carga o carga en cada nodo (CARGA) y carga máxima del camión (CG).
Salida: Vector inicial (VI)

Etapa 1. i=Número de nodos sin incluir el centro de acopio;
J=0;
VI=0;
Etapa 2. Repetir hasta i;
{
Etapa 3. Se determina el nodo más cercano al nodo N_{i-1}, obteniendo el nodo $N_{i;}$
Etapa 4. Guardar carga como J=J+CARGA(N_i);
Etapa 5. VI=[VI, N_i]
Etapa 6. Si CARGA ≥ CG, entonces
VI=[0, N1,…, 0, N_i]
}
Etapa 7. Parar y reportar VI=[VI, 0]

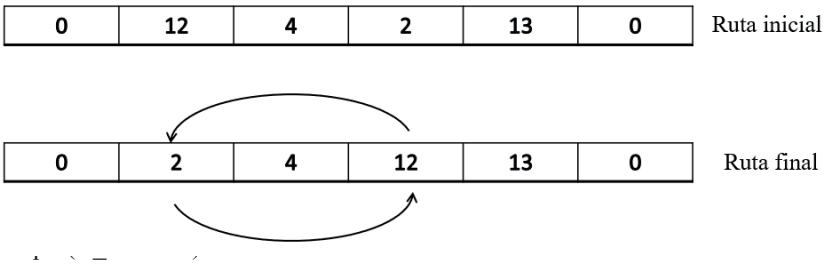
Figura 1. Vector Inicial

3.3.3 Evaluación de la solución

La función objetivo es la ecuación (1) la cual busca minimizar costo relacionado con transporte y tiempo de espera por llegar fuera de la ventana de tiempo.

El primer término de la ecuación (1), el costo total asociado a la distancia total recorrida se halla de la siguiente manera: primero se calcula la distancia total recorrida (J). El costo de transporte, C_TRANS se multiplica por la distancia total, DIS_T=DIS(1) +DIS(2)…DIS(n)).

El segundo y tercer término de la ecuación (1), el costo total asociado por llegar fuera de la ventana de tiempo. Se procede de la siguiente manera: asumiendo que el tiempo de carga es C. Se comienza determinando la distancia acumulada DIS_T=DIS(1)+C+DIS(2)+C, luego se analiza en el nodo N2 si la suma anterior está dentro de la ventana de tiempo, si se encuentra ahí, no hay costo asociado por llegar a deshora, no obstante, si esta fuera de la ventana de tiempo, se analiza si está por debajo o por encima de la ventana de tiempo, si está en el primer caso se guarda como VT_EARLY, si es el segundo caso, se guarda como VT_LATER, se repite el proceso para el nodo N3, comprendiendo que la distancia acumulada general se expresa de la siguiente manera: DIS_T=DIS(1)+DIS(2)+…+ DIS(n)+(n*C), donde n es el nodo que se está analizando sin contar la fábrica (nodo 0). El pseudocódigo se muestra en la Figura 2.



Salida: C_TOTAL.

Etapa 1. i=diámetro(VI)-2;
DIS_T=0;
H=0;
VT_EARLY=0;
VT_LATER=0;
Etapa 2. Repetir hasta i;
{
Etapa 3. Determinar DIS_T=DIS_T+ $DIS_{(i,i-1)}$;
Etapa 4. Hallar H=H+(J/VP);
Etapa 5. Si H < $HLL_{(i)}$, entonces VT_EARLY= VT_EARLY+H;
Else if Si H < $HS_{(i)}$, entonces VT_LATER = VT_LATER +H;
}
Etapa 7. Parar y reportar C_TOTAL=(DIS_T*C_TRANS)+(VT_EARLY*C_EARLY)+(VT_LATER*C_LATER);

Figura 2. Costo

3.4 Estructura de vecindario

Se utiliza una estructura de vecindario simple. En el vector no se modifica el primer y último nodo. Los vecinos se generan intercambiando las posiciones de dos nodos de una misma ruta (ver Figura 3).

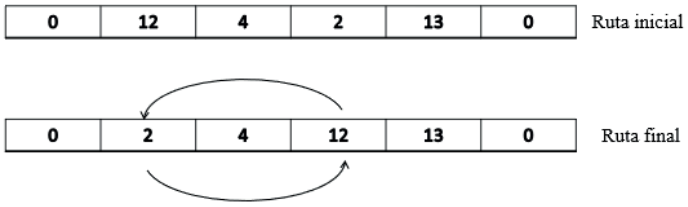


Figura 3. Vecindario generado en una ruta

Después de realizar el cambio se procede a analizar cada ruta, y aquellas que no cumplan la restricción de carga máxima, se transforma en 2 veces el valor máximo del vector de costo (C_ALL), garantizando así que no se pueda seleccionar como la solución de la iteración. Después se localiza el menor elemento (m) en el vector C_ALL sin incluir el primer elemento dado que este está asociado al vector inicial.

3.4.4 Lista Tabú

La Lista Tabú impide que se repita soluciones que permitirían salir de un óptimo local. Después de obtener la ruta que tenga el menor costo asociado, se guarda dicho vector VI_T(:,m) en la Lista Tabú. Los vectores que están en la Lista Tabú quedan prohibidos, sin embargo, para saber si el nuevo vector determinado está en la Lista Tabú, se procede a restar VI con cada vector de la Lista Tabú, si, y solo si el resultado es un vector de ceros, se puede asegurar que es el mismo, convirtiendo su costo asociado en 2 veces el valor máximo del C_ALL actual, garantizando así que no se pueda seleccionar ningún vector de la Lista Tabú, posterior a esto se procede a determinar el costo y localización del menor elemento en el vector C_ALL resultante (nuevo m) sin incluir al primer elemento. Dicha localización permite encontrar su respectiva ruta VI_T(:,(nuevo m)), siendo este el nuevo VI, este proceso se repite el número de iteraciones, i. . Cada ruta se va almacenando en una matriz llamada RUTA y el costo asociado en un vector llamado GRAF. Al final del proceso, se localiza el escalar más pequeño. pequeño en COSTO3 y su vector asociado en la matriz RUTA, siendo esta la mejor solución.

4 Resultados y análisis

Para validar el comportamiento del Algoritmo se utilizaron tres ejemplos. El primero, fue propuesto por Ma, y Wei, (2013). El segundo y tercero se generaron aleatoriamente a partir del primero, pero cambiándole la cantidad de proveedores, n, siendo 25 y 50 respectivamente. En la Tabla 1 se muestran las características de los ejemplos que permanecen constantes en los tres ejemplos tales como los costos de penalización por llegar fuera de la ventana de tiempo, costo de transporte y tiempo de servicio.
Tabla 1. Parámetros iguales en los tres ejemplos

Notaciones	Valores	Unidad
α	15	km/hora
$\boldsymbol{\lambda}$	12	yuanes/hora
μ	13	yuanes/hora
T_i	0.25	hora

En la Tabla 2 se muestran los parámetros que se generaron con distribución de probabilidad uniforme para el segundo y tercer ejemplo.

Tabla 2. Parámetros generados mediante distribución de probabilidad

Notaciones	Valores	Unidad
$\boldsymbol{\mu_i}$	[3, 14]	m^3
$\boldsymbol{a_i}$	[6.50, 12.50]	hora
$\boldsymbol{b_i}$	[7.7, 12.]	hora
X Y	[5, 65]	Km

En la Tabla 3 se muestran los parámetros que permanecieron iguales en el segundo y tercer ejemplo.

Tabla 3.Parámetros iguales en el segundo y tercer ejemplo

Notaciones	Valores	Unidad
V	60	m^3
v	60	Km/hora
$\boldsymbol{X_0, Y_0}$	[35, 35]	Km

Se realizaron unas pruebas iniciales y se determinaron que los parámetros del Algoritmo de Búsqueda Tabú para cada uno de los ejemplos tal como se muestra en la Tabla 4.

Tabla 4. Parámetros del Algoritmo de Búsqueda Tabú

Notaciones	Posiciones	Lista tabú	Iteraciones
Ejemplo 1	3-4	5	50
Ejemplo 2	3-4	5	50
Ejemplo 3	4-5	50	100

Se realizaron 10 corridas del Algoritmo de Búsqueda Tabú para cada ejemplo y a continuación se muestra la mejor solución encontrada.

A partir de los resultados presentados en la Tabla 5 se puede evidenciar como el porcentaje de utilización de vehículos es mayor cuando se aplica Búsqueda Tabú (TS) comparado al Algoritmo de Optimización por Enjambre de Partículas (PSO).

Tabla 5. Comparación entre el PSO y TS en términos de distancia y utilización.

Algoritmo	Vehículo	Ruta del vehículo	Distancia Total (Km)	Volumen (m^3)	% Utilización
PSO	1	0-13-15-0	61,59	23	77
	2	0-6-14-5-0	74,16	25	83
	3	0-2-8-7-11-10-0	117,95	30	100
	4	0-12-4-0	55,81	10	33
	5	0-3-9-1-0	69,38	17	57
TS	1	0-2-7-11-10-0	105,92	25	83
	2	0-4-15-14-0	101,98	29	97
	3	0-12-13-5-6-0	63,17	29	97
	4	0-1-9-3-0	70,40	27	90
	5	0-8-0	52,50	5	17

En la Tabla 6 se evidencia que, aunque existe una mayor distancia recorrida por el Algoritmo de Búsqueda Tabú el costo total es menor en comparación al Algoritmo PSO, este costo se logra con menos iteraciones del Algoritmo.

Tabla 6. Distancia y costo total

Algoritmos	Vehículos utilizados	Iteraciones	Distancia total de transporte (km)	Costo Total
PSO	5	50	378,89	7292,4
TS	5	140	393,97	6710,9

En la Tabla 7 se evidencia que existe mayor utilización de los vehículos cuando se tienen 50 proveedores.

Tabla 7. Resultados en términos de Distancia y utilización

Algoritmo	Vehículo	Ruta del vehículo	Distancia Total (Km)	Volumen (m^3)	% Utilización
Ejemplo 2	1	0-2-9-1-12-5-19-0	88,47	47	78
	2	0-13-3-24-22-14-8-4	80,39	58	97
	3	0-10-25-11-7-16-21-0	70,34	53	88
	4	0-15-6-17-18-23-0	68,61	58	97
	5	0-20-0	72,14	14	23
Ejemplo 3	1	0-3-28-25-16-48-0	85,84	12	20
	2	0-29-33-27-44-43-0	117,45	59	98
	3	0-50-6-21-45-32-38-0	136,16	50	83
	4	0-42-22-34-35-39-4-7-24-0	193,73	53	88
	5	0-40-10-8-9-13-26-36-41-0	183,73	45	75
	6	0-15-47-18-31-1-23-5-12-0	134,55	56	93
	7	0-37-2-14-19-14-49-0	113,94	57	95
	8	0-20-11-30-46-0	128,58	27	45

En la Tabla 8 se evidencia que para atender el doble de proveedores (n=50) solo se necesitaron tres vehículos adicionales comparado con el ejemplo 2 y así mismo el costo total se duplica.

Tabla 8. Distancia y costo total del ejemplo1 y ejemplo 3

Algoritmos	Vehículos utilizados	Distancia total de transporte (km)	Costo Total
Ejemplo 2	5	379,94	7445,92
Ejemplo 3	8	1093,98	20155,86

El problema de ruteo de vehículos Milk Run con ventanas de tiempo es complejo, de carácter NP-hard con amplias aplicaciones en la logística de abastecimiento entre un comprador y varios proveedores que mantienen una relación de cooperación en la cadena de suministro. La complejidad de instancias de mayor tamaño hace necesario implementar Metaheurísticas para proveer soluciones aproximadas en tiempo computacional razonable. Esta investigación propone un Algoritmo de Búsqueda Tabú para resolver MRVRPTW.

Para demostrar la efectividad del algoritmo se comparó con un problema propuesto por Ma, y Wei, (2013), el cual lo resolvían por el Algoritmo de Optimización por Enjambre de partículas, encontrando un costo menor 6710,9 y llegando al resultado en menos iteraciones, 50. Por otro lado, con el fin de analizar que pasaría si el número de proveedores aumenta, se encontró que el costo total con 25 proveedores es similar al de 15 pero cuando estos aumentan a 50 el costo total se duplica.

Este trabajo puede ser extendido al considerar emisiones de carbono en la función objetivo. Adicionalmente, considerar productos perecederos de vida útil fija para abordarlo en contexto de otros tipos de productos que sean de rápido movimiento como leche, productos agrícolas

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Periodic vehicle routing with consistency and synchronization constraints for nanostore fulfilment in emerging markets

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Abstract. In this paper we introduce the presale strategy for nanostore fulfilment in emerging markets, explaining current strategies and proposing one where resources are routed simultaneously. We study this problem as an extension of the periodic vehicle routing problem with consistency and synchronization constraints. To solve this problem, we propose a Mixed Integer Linear Programming (MILP) formulation and a Metaheuristic Algorithm. We compare the MILP results against a two phase method that mimics current strategy and show a cost reduction of 3,04% in small instances (with 10 clients).

Keywords: periodic vehicle routing problem · Consistency · Synchronization · MILP · VND · nanostore delivery

1 Introduction

The most common scheme to retail products urban delivery in emerging markets is the traditional channel, composed by small business units, known as nanostores, operated by the same family members and usually with one single store [5]. These types of stores fit well to their consumers' needs because of their location and the small-scale product presentation which allows buying a daily portion [3]. The logistic process required to serve all those nanostores working under the traditional scheme is complex because there is a large number of delivery points and their small drop size. As an alternative to face this complex environment, companies operating in emerging markets resort to the so-called "presale" strategy where a seller visits each store to contact the store owner, take their orders, evaluate the product they offer, introduce sale promotions and guarantee the visibility of their products on the shelves [5]. To foster a good relationship between the seller and the store owner, it is important to keep the same seller attending each client. Usually, the delivery of the products ordered by the nanostore is carried the day after the preseller visit by a fleet of trucks. Current practices indicate that most of the times, those operations are managed

by different departments inside the enterprise: the sales department is in charge of the assignment and routing of the presellers whereas the logistics department is in charge of the trucks routing. This detachment may cause extra costs, feasibility problems and reprocessing of already made routes. Therefore, in this abstract, we propose to take both decisions simultaneously, avoiding those types of problems and finding solutions with minor cost.

To model the integrated planning of the presale and deliveries, we introduce the periodic vehicle routing problem with consistency and synchronization (ConSyncPVRP). This problem combines the attributes of the periodic vehicle routing problem (PVRP) [6], person-oriented consistency [8] and operation synchronization [4].

2 Problem Definition

The problem consists in deliver goods to a set of nanostores on a time horizon, where each one must be visited by two different resources: one preseller and one truck. Each customer has a given frequency (i.e., number of days that must be visited) and a demand for the whole planning period. Visiting days are grouped in so-called scenarios, (i.e, subsets of days), that serve to assign customers to delivery days. To assign a customer to a given scenario the number of visiting days of the scenario must be equal to the delivery frequency of the customer. The objective function of this problem is to minimize the total costs. There are two types of costs: fixed costs, which increase with every resource used, and variable costs, which increase with every distance unit traveled. The constraints we have to fulfill are: (i) every resource has to start and finish its trip at the depot, (ii) each nanostore should be assigned to a periodic scenario with the same number of visits than its required frequency, (iii) the preseller has to be consistent for every client, it means the presale visit has to be always made by the same preseller, (iv) there is operation synchronization between the resources: trucks must deliver to the nanostores the day after the presale visit, (v) the total load of every resource must not surpass its capacity, (vi) every resource must arrive at the depot before a daily time limit, (vii) Gavish and Graves sub-tour elimination constraints [1], and (viii) symmetry breaking constraints.

3 Solution Methods

To solve the ConSyncPVRP we propose two methods. The first one is a mathematical programming model whereas the second one is a three-phase metaheuristic to solve large instances.

MILP formulation: We built a mathematical programming model using a mixed integer linear programming (MILP) formulation in AIMMS software. In order

to test it, we adapted the instances of PVRP from [2] and solved 147 instances with 10 clients, 20 with 20 clients and 20 with 40 clients making a total of 187 instances. From the 187 instances only 84% were feasible. In a time lapse of an hour, we optimally solved all the 10-clients feasible instances but only 10% of the 20-clients feasible instances and none of the 40-clients feasible instances. As a benchmark, we compare the optimal solutions of the MILP formulation with 10-clients against a two stage approach that mimics the current practice by optimally solving the preseller decisions first and the vehicles decisions after. Our solution has an average cost decrease of 3,04%. The mean gap, the distance between the lower bound and the best integer solution, was 14,04% for the 20-clients instances and above 60% for the 40-clients instances. This results shows that the MILP formulation solve problem with less than 20 clients in a reasonable computational time and that the two-stage approach used by practitioners to tackle this problem currently leads to infeasibilities and extra costs.

Metaheuristic algorithm: For larger instances, we built a metaheuristic method with three components: a randomized constructive heuristic, a repairing heuristic and a variable neighborhood descend (VND) with five different neighborhoods, shown in Fig. 1. The randomized constructive heuristic builds a solution by randomly choosing a scenario and a pair of resources for each client (to insert the customer into their routes). This method assures the consistency in the preseller

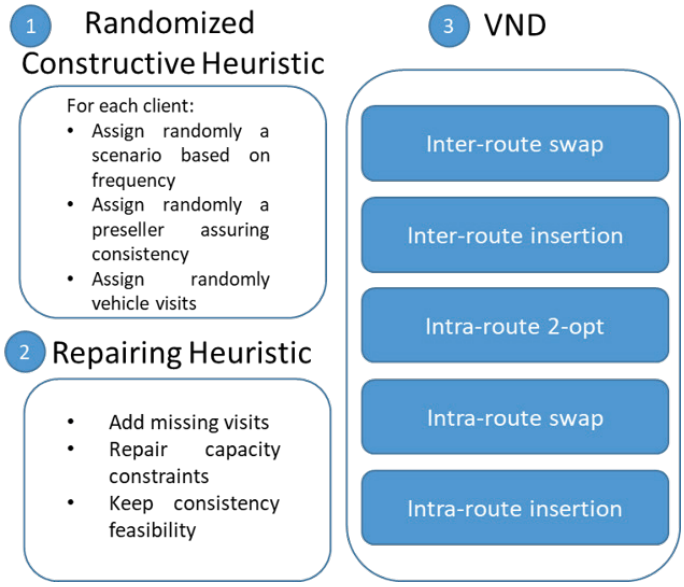

Fig. 1. Three-component metaheuristic representation

routing but some solutions could have feasibility problems with the capacity constraint of the vehicle. Then, the repairing heuristic tries to solve the infeasibility issue with two mechanisms. The first one examines which client has the least cost when changing its resources. If the possible resources are not available (all resources surpass their capacity), the second mechanism tries the least cost scenario change between all clients of the infeasible route. The repairing heuristic stops when all routes are feasible or after a given number of trials. If after a number of trials, the solution is still infeasible, it is discarded.

Finally, the VND improves the solution reducing the total cost. It contains five neighborhoods, the first two of them changes two routes at the same time meanwhile the last three operate over one route. The set of neighborhoods are: (i) inter-route swap of two customers, (ii) inter-route insertion of a customer, (iii) intra-route swap, (iv) intra-route insertion of a customer and (v) intra-route 2-opt [7]. This method is currently under development and computational testing. Results will be presented in the conference.

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Nueva representación para la resolución simultánea del batching y scheduling en una planta batch multiproducto

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Resumen. El gran número de trabajos abordando el problema de scheduling en plantas batch deja en evidencia su importancia para lograr una operación eficiente de la planta, como así también su dificultad y el número de variantes que se pueden presentar. Usualmente el scheduling ha sido resuelto de manera simplificada, teniendo como datos el número y tamaño de batches (o lotes) necesarios para satisfacer la demanda. Más recientemente, han sido desarrollados modelos que resuelven simultáneamente el problema de batching, o sea determinar el número y tamaño de los lotes, y scheduling, logrando en general mejores soluciones. Sin embargo estos modelos son de una gran complejidad computacional, debido a su naturaleza combinatoria, por lo que lograr el desarrollo de modelos eficientes que permitan abordar problemas de gran tamaño continúa siendo un desafío. En este trabajo se presenta un novedoso modelo de programación mixta entera lineal (MILP) para la resolución simultánea del batching y scheduling en una planta batch multietapa, con unidades distintas operando en paralelo y fuera de fase en cada etapa.

Palabras clave: Planta batch multiproducto, Batching, Scheduling, Tiempos discretos.

1 Introducción

En la industria de procesos, tienen un rol destacado las plantas de producción batch debido a la flexibilidad de las mismas para procesar varios productos y en diferentes cantidades utilizando el mismo equipamiento. En este tipo de plantas el scheduling de la producción juega un papel fundamental para lograr un funcionamiento eficiente. Numerosos trabajos han abordado dicho problema durante las últimas tres décadas, cubriendo aspectos teóricos, diferentes representaciones y métodos de solución, cuyo alcance ha sido detallado en exhaustivos reviews ([1], [2], [3], [4]).

En ambientes de producción secuencial (plantas flowshop), la mayoría de los modelos presentados en la literatura resuelven en una primera etapa el problema de "batching", es decir, determinan el número y tamaño de los batches necesarios para satisfacer las órdenes y la solución de ese problema es usada en una segunda etapa como dato en el problema de scheduling, el cual consiste entonces en determinar la asignación, secuenciamiento y los tiempos de inicio y fin de la operación de los lotes que se

deben procesar. Dicha descomposición del problema se ha realizado, principalmente, a causa de la complejidad del mismo; sin embargo, debido a la estrecha relación existente entre los problemas de batching y scheduling, las soluciones obtenidas resolviendo el problema en dos fases pueden resultar muy inferiores en comparación a las que se obtienen al resolver ambos problemas de manera simultánea. Esta diferencia en las soluciones resulta especialmente notoria en el caso de plantas multiproducto que cuentan con unidades diferentes operando en paralelo y fuera de fase en cada etapa. Prasad y Maravelias [5] han presentado el primer enfoque que considera la optimización simultánea de ambas decisiones, y desde entonces algunos enfoques en esta área, con ciertas limitaciones y características, han sido presentados ([6], [7]). Más recientemente, Fumero y col. [8] han desarrollado un modelo de programación mixta-entera lineal (MILP) basado en slots para optimizar simultáneamente las decisiones de batching y scheduling para una planta batch multiproducto multietapa que opera a través de campañas de producción mixtas. Los trabajos mencionados recientemente, como así también la gran mayoría de modelos propuestos para el problema de scheduling en este tipo de ambientes, adoptan una representación continua del tiempo. Un primer modelo de tiempo discreto que integra las decisiones de batching y scheduling en plantas secuenciales ha sido propuesto por Sundaramoorthy y col. [9], donde los autores enfatizan algunas ventajas de esta representación frente a las de tiempo continuo, presentando flexibilidad para incorporar el modelado de diversas características del proceso tales como tiempos de transición, niveles de inventario, recursos limitados, operaciones de mantenimiento, etc. Más aún, estudios recientes han mostrado que los modelos de tiempo discreto son más efectivos, desde el punto de vista computacional, para problemas de gran escala (Merchan y col. [10]).

Sobre ambientes de producción secuencial, pero más generales, como es el caso de plantas batch multipropósito, Lee y Maravelias [11] han desarrollado modelos de scheduling con representación de tiempo discreto, considerando almacenamiento intermedio finito. Posteriormente, estos autores propusieron formulaciones MILP de tiempo discreto para optimizar simultáneamente las decisiones de batching y scheduling en este contexto, introduciendo un mecanismo de agrupación de unidades en conjuntos que son capaces de procesar cierto rango de tamaños posibles de los batches ([12]).

En este trabajo se desarrolla un novedoso modelo MILP para la resolución simultánea de los problemas de batching y scheduling en una planta secuencial, multiproducto, que cuenta con unidades diferentes operando en paralelo en cada etapa y que no admite almacenamiento intermedio. Se introduce por primera vez el concepto de camino de producción, llamando así a cada una de las posibles trayectorias de un batch a través de una secuencia de unidades en la planta, una de cada etapa. De esta manera, con una única decisión, es posible asignar un batch a todas las unidades en que será procesado para obtener el producto deseado. Esta representación facilita la determinación del tamaño posible del batch sobre ese camino, como así también los cálculos de tiempos. Teniendo en cuenta que sólo se debe determinar el tiempo de procesamiento inicial de cada batch en la unidad correspondiente a la primera etapa, se adopta una representación de tiempo discreto. En general, el problema consiste en determinar el número de batches que se deben procesar para satisfacer la demanda conocida de un conjunto de órdenes, hallar el secuenciamiento de los mismos y los

tiempos iniciales y finales de procesamiento de cada batch de modo que se minimice el makespan, es decir el tiempo total de procesamiento.

2 Descripción del problema

En este trabajo se aborda la solución simultánea de los problemas de batching y scheduling para el caso de una planta de producción batch multiproducto, compuesta por múltiples etapas $j \in J$, donde cada una de ellas cuenta con unidades $k \in KJ_j$ de diferentes tamaños operando en paralelo y fuera de fase.

La planta debe procesar órdenes $d \in D$ por una cantidad Q_d, las cuales pueden ser satisfechas por uno o varios batches de diferentes tamaños. Cada orden monoproducto tiene asociada una fecha de emisión a partir de la cual puede comenzar a procesarse, denotada por RD_d, y otra para la cual debe completarse, denominada DD_d.

El tamaño V_k de cada unidad $k \in KJ_j$, el tiempo de procesamiento t_{dk} de cada batch que se procese para la orden d en la unidad k, el factor de tamaño SF_{dj}, que indica el tamaño requerido en la etapa j para producir una unidad de masa de d como así también el porcentaje mínimo de uso en cada unidad k para procesar un batch de la orden d, indicado con α_{dk}, son parámetros del problema.

Cada batch debe ser procesado siguiendo la misma serie de etapas y no se permite el almacenamiento intermedio. Por lo tanto se adopta la política de transferencia de espera cero (Zero-Wait o ZW), es decir, cada batch que ha sido procesado en una etapa debe ser transferido inmediatamente a la siguiente. El tiempo requerido para realizar dicha transferencia se considera despreciable.

El problema consiste en determinar el número de batches que se deben procesar para satisfacer la demanda de cada orden, las unidades en que se procesa cada batch y realizar el secuenciamiento de los batches calculando el tiempo inicial y final de procesamiento de cada uno de ellos en cada una de las unidades, teniendo como objetivo minimizar el tiempo total requerido para procesar completamente todas las órdenes, es decir, minimizar el makespan.

3 Formulación del modelo

En este trabajo se considera una planta batch secuencial, donde cada batch debe seguir la misma secuencia a través de todas las etapas de la planta y ser procesado en exactamente una unidad de cada etapa. Cada batch se trata de manera individual durante el procesamiento, es decir, no se divide ni se mezcla con otros batches. A partir de las condiciones anteriores surge la propuesta de que durante su procesamiento cada batch sigue un camino pasando por una unidad en cada etapa. Formalmente se define un camino de producción $r \in R$ como una $|J|-upla$ de la forma $(k_1, k_2, \ldots, k_{|J|})$ donde $k_1 \in KJ_1, k_2 \in KJ_2, \ldots, k_{|J|} \in KJ_{|J|}$. Por lo tanto, el número total de caminos posible resulta $|R| = \prod_{j=1}^{j=|J|} |KJ_j|$.

El concepto de camino, que se introduce por primera vez en este trabajo, permite una simplificación importante en la formulación del modelo, ya que al asignar un batch a un camino se está realizando la asignación simultánea del mismo a todas las unidades donde se procesará, a diferencia de las formulaciones previas que asignan los batches a cada unidad de manera individual.

Puesto que son conocidos el volumen de cada unidad, su porcentaje mínimo de ocupación y el factor de tamaño de cada orden en las diferentes etapas, es posible determinar los tamaños mínimo y máximo factibles en cada camino para un batch de cada orden, lo cual permite plantear restricciones para satisfacer la demanda sin tener que determinar explícitamente el tamaño de cada batch.

Por último, pero no menos importante, dado que la planta opera con política de transferencia zero-wait (ZW), basta con conocer el tiempo en el cual se comienza a procesar cada batch en el camino al que se asignó para que queden completamente determinados los tiempos en que el batch se procesará en cada unidad del camino y el tiempo final de procesamiento. Esto permite adoptar una representación de tiempos discretos donde se propone una grilla con los posibles tiempos de inicio de procesamiento en cada camino, evitando de esta manera introducir variables para la determinación del tiempo de inicio de procesamiento en cada unidad.

3.1. Cotas para el número de batches

Se define el conjunto KR_r que contiene las unidades que conforman el camino r. Entonces, los tamaños mínimo y máximo que admite el camino r para un batch de la orden d están dados, respectivamente, por las siguientes expresiones:

$$B_{dr}^{\min} = \max_{j \in J} \left\{ B_{drj}^{\min} \right\} \qquad \forall d \in D, r \in R$$

$$B_{dr}^{\max} = \min_{j \in J} \left\{ B_{drj}^{\max} \right\} \qquad \forall d \in D, r \in R$$

donde

$$B_{drj}^{\min} = \alpha_{dk} \frac{V_k}{SF_{dj}} \qquad \forall d \in D, r \in R, j \in J, k \in KR_r, k \in KJ_j$$

$$B_{drj}^{\max} = \frac{V_k}{SF_{dj}} \qquad \forall d \in D, r \in R, j \in J, k \in KR_r, k \in KJ_j$$

Notar que los parámetros B_{drj}^{min} y B_{drj}^{max} están bien definidos ya que para cada etapa j, existe una única unidad k asociada al camino r.

Debido a que las unidades de la planta son de diferentes tamaños, tienen porcentaje mínimo de ocupación y se consideran distintos factores de tamaño para cada orden, puede ocurrir que el tamaño máximo admisible en una unidad sea menor que el tamaño mínimo determinado para otra unidad del mismo camino. Obviamente, no es posible procesar un batch de esa orden en ese camino. En ese caso, resulta que

$B_{dr}^{\min} > B_{dr}^{\max}$. Por lo tanto, se define para cada orden d el conjunto FAC_d de todos los caminos r en los cuales es posible procesar un batch de esa orden, es decir, en los que cuales $B_{dr}^{\min} \le B_{dr}^{\max}$.

A partir de los tamaños factibles para los batches de las diferentes órdenes en cada camino, resulta que los tamaños mínimo y máximo admisibles para cada batch de la orden d en la planta están dados por:

$$B_d^{\min} = \min_{r \in FAC_d} \left\{ B_{dr}^{\min} \right\} \qquad \forall d \in D$$

$$B_d^{\max} = \max_{r \in FAC_d} \left\{ B_{dr}^{\max} \right\} \qquad \forall d \in D$$

Luego, los números mínimo y máximo de batches en que puede ser dividida cada orden son, respectivamente:

$$NB_d^{\min} = \left\lceil \frac{Q_d}{B_d^{\max}} \right\rceil \qquad \forall d \in D$$

$$NB_d^{\max} = \left\lfloor \frac{Q_d}{B_d^{\min}} \right\rfloor \qquad \forall d \in D$$

donde se han usado las funciones piso y techo para obtener el número entero.

El número de batches que se procesarán para satisfacer la orden d es una variable del problema, por lo que se propone el conjunto N_d de números enteros positivos comprendidos entre $NB_d^{\min}$ y $NB_d^{\max}$, de los cuales sólo uno será seleccionado. Para representar esta selección, se introduce la siguiente variable binaria:

$$x_{dn} = \begin{cases} 1 & \text{si la orden } d \text{ es dividida en } n \text{ batches} \\ 0 & \text{en otro caso} \end{cases}$$

la cual debe satisfacer la ecuación

$$\sum_{n \in N_d} x_{dn} = 1 \quad \forall d \in D \tag{1}$$

3.2. Asignación de los batches a los caminos

Los diferentes batches b que se utilizarán para satisfacer la orden d, se identifican, según el número requerido n de ellos, de la siguiente manera: si la orden d se procesa en un único batch (n = 1), éste se indica como *b1*; si se divide en dos batches (n = 2), se denominan *b1* y *b2*; y así sucesivamente. Para formalizar lo anterior, para cada orden d y número de batches n que se utilicen para su procesamiento, se introduce el conjunto DB_{dn}={*b1,b2,...bn*}.

Cada batch b requerido para completar la orden d se asigna a un único camino r, a través de la variable

$$z_{dnbr} = \begin{cases} 1 & \text{si la orden } d \text{ es dividida en } n \text{ batches y el batch } b \text{ es} \\ & \text{asignado al camino } r \\ 0 & \text{en otro caso} \end{cases}$$

Teniendo en cuenta los tamaños admisibles en cada camino, el tamaño de la orden y el número de batches en que ésta se puede dividir para ser procesada, no todas las combinaciones de asignación batch-camino resultarán factibles. El objetivo es construir para cada orden d, número de batches n en que se divide y batch b que se procesa, el conjunto POS_{dnb} que contenga sólo los caminos r a los que efectivamente es posible asignar el batch b.

Antes de plantear el caso general se introduce un ejemplo sencillo pero esclarecedor: se considera una planta que cuenta con tres caminos *r1*, *r2* y *r3* en los cuales se pueden procesar batches cuyo tamaño (en kg) se encuentra entre 140 y 210, 80 y 120, 60 y 90, respectivamente. Se debe procesar una orden de 190 kg. Las posibles soluciones son:

a) procesar un único batch *b1* en el camino r1 ($n = 1$).

b) la orden se divide en dos batches *b1* y *b2* ($n = 2$). Acá es posible realizar la asignación de dos maneras: ambos batches a *r2* (ya que $80+80 \leq 190 \leq 120+120$), o bien un batch a *r2* y el otro a *r3* ($60+80 \leq 190 \leq 90+120$). Todas las demás asignaciones con dos batches resultan no factibles. Cabe remarcar que en el segundo caso es posible asignar *b1* a *r2* y *b2* a *r3* o viceversa. Dado que ambas soluciones son equivalentes, se adopta realizar la asignación en forma creciente, es decir, el batch con una etiqueta menor se asigna al camino menor, en este caso *b1* a *r2* y *b2* a *r3*.

c) la orden se divide en tres batches *b1*, *b2* y *b3* ($n = 3$); en este caso los tres batches deben ser asignados al camino *r3* ($3*60 \leq 190 \leq 3*90$), todas las demás asignaciones resultan no factibles.

Por lo tanto, en este caso los conjuntos POS_{dnb} antes descriptos resultan:

a) en caso de hacer un solo batch $POS_{d,1,b1} = \{r1\}$;

b) si se hacen dos batches $POS_{d,2,b1} = \{r2\}$, $POS_{d,2,b2} = \{r2,r3\}$;

c) por último si se hacen tres batches $POS_{d,3,b1} = POS_{d,3,b2} = POS_{d,3,b3} = \{r3\}$.

Planteando el caso general, resulta que únicamente es posible procesar la orden d dividida en n batches $b1, b2, \ldots, bn \in DB_{dn}$ asignados a los caminos $r_{m1}, r_{m2}, \ldots, r_{mn} \in FAC_d$ (los cuales pueden estar repetidos) si se cumple que $\sum_{h=1}^{n} B_{dr_{mh}}^{\min} \leq Q_d \leq \sum_{h=1}^{n} B_{dr_{mh}}^{\max}$. Dentro de cada una de estas asignaciones factibles se selecciona la que realiza la asignación batch-camino en forma creciente, descartando las soluciones equivalentes, como se ha detallado en el ejemplo. A partir de todas las asignaciones batch-camino que satisfagan las condiciones anteriores se crean los conjuntos POS_{dnb} cuyos elementos son los caminos r a los que efectivamente es posible asignar el batch b si la orden d se divide en n batches para ser procesada. La introducción de dichos conjuntos reduce notablemente la combinatoria del problema de asignación batch-camino, especialmente cuando los tamaños admisibles en los caminos de la planta difieren entre sí. Además este preprocesamiento se puede realizar antes de resolver el problema a partir de los datos disponibles.

La siguiente ecuación asegura que cada batch que se utilice para satisfacer una orden sea asignado a un único camino para su procesamiento:

$$\sum_{r \in POS_{dnb}} z_{dnbr} = x_{dn} \qquad \forall d \in D, n \in N_d, b \in DB_{dn} \tag{2}$$

Con el fin de evitar soluciones redundantes, la asignación batch-camino se realiza en forma creciente, es decir si los batches $b, b' \in DB_{dn}$ con $b' < b$ son asignados a los caminos $r, r' \in FAC_d$ donde $r' < r$, entonces b se asigna a r y b' a r'

$$\sum_{\substack{r' \in POS_{dnb+1} \\ r' < r}} z_{dnb+1r'} \leq 1 - z_{dnbr} \qquad \forall d \in D, n \in N_d, n \geq 2, b, b+1 \in DB_{dn}, r \in POS_{dnb} \tag{3}$$

3.3. Restricciones de tiempo y secuenciamiento

En este modelo se utiliza una representación de tiempo discreto, en la cual se propone una grilla equiespaciada de puntos $t \in T$ teniendo en cuenta las fechas de emisión y entrega de las órdenes. Para simplificar la representación se supone que el menor de los tiempos de inicio es igual a 0 y los demás tiempos de inicio y fechas de entrega se proponen respecto a dicho tiempo inicial. El paso Δt de la grilla es igual al máximo común divisor entre los tiempos de procesamiento de todas las órdenes en cada una de las unidades.

Si se procesa un batch de la orden d en el camino r el tiempo total de procesamiento del mismo es

$$t_{dr} = \sum_{k \in KR_r} t_{dk} \qquad \forall d \in D, r \in FAC_d$$

con lo cual sus posibles tiempos de inicio $t \in TDR_{dr}$ son aquellos que satisfacen: $RD_d \leq t \leq DD_d - t_{dr}$.

Se introduce la variable binaria y_{dnbrt}:

$$y_{dnbrt} = \begin{cases} 1 & \text{si la orden } d \text{ es dividida en } n \text{ batches y el batch } b \text{ se comienza} \\ & \text{a procesar en el camino } r \text{ en el punto de tiempo } t \\ 0 & \text{en otro caso} \end{cases}$$

Se debe asignar cada batch procesado a un único tiempo de inicio, lo cual se impone a través de la siguiente ecuación

$$\sum_{t \in TDR_{dr}} y_{dnbrt} = z_{dnbr} \qquad \forall d \in D, n \in N_d, b \in DB_{dn}, r \in POS_{dnb} \tag{4}$$

El secuenciamiento de batches se realiza de manera implícita imponiendo que en cada unidad y en cada punto de la grilla de tiempos se puede procesar como máximo un batch. Además, esto evita el solapamiento en los procesamientos de batches en

cada unidad de la planta. El modelo determina únicamente el tiempo inicial de operación de cada batch en la primera unidad del camino donde se procesa. Por lo tanto, para determinar en qué puntos de tiempo se procesa en las unidades del camino que no pertenezcan a la primera etapa, deben tenerse en cuenta el tiempo de inicio y los tiempos de procesamiento en las unidades previas del camino.

Sea d una orden y $r \in FAC_d$, $r = (k_1, k_2, ..., k_j, ... k_{|J|})$ con $k_1 \in KJ_1$, $k_2 \in KJ_2$, … $k_j \in KJ_j$,… $k_{|J|} \in KJ_{|J|}$, un camino de producción en el cual es posible procesar un batch de la orden d. Para cada unidad k que compone el camino r, se definen los parámetros TL_{drk} y TU_{drk}, que corresponden a los tiempos totales de procesamiento de cualquier batch de la orden d hasta la unidad k y hasta la unidad anterior a ésta en el camino, respectivamente:

$$TL_{drk} = \sum_{j'=1}^{j} \sum_{\substack{k' \in KJ_{j'} \\ k' \in KR_r}} t_{dk'} \qquad \forall d \in D, j \in J, k \in KJ_j, r \in FAC_d, r \in RK_k$$

$$TU_{drk} = \sum_{j'=1}^{j-1} \sum_{\substack{k' \in KJ_{j'} \\ k' \in KR_r}} t_{dk'} \qquad \forall d \in D, j \in J, j \geq 2, k \in KJ_j, r \in FAC_d, r \in RK_k$$

con $TU_{drk} = 0 \; \forall \; d \in D, j = 1, k \in KJ_1, r \in FAC_d, r \in RK_k$, siendo RK_k el conjunto de caminos que pasan por la unidad k.

Sea t un punto genérico de la grilla de tiempos propuestos y k_j la unidad sobre la etapa j que corresponde al camino r. Para determinar si un batch de la orden d inicia su procesamiento o se esté procesando en el tiempo t en la unidad k_j, se deben calcular los posibles tiempos de inicio de operación para el batch en la unidad k_1 correspondiente a la primera etapa de la planta. Como se puede observar desde la Figura 1, el tiempo más tardío de inicio en la unidad k_1 para que el batch de la orden d inicie su procesamiento en el tiempo t en la unidad k_j se calcula como $t - TU_{drk_j}$, mientras que el tiempo más temprano de inicio en la unidad k_1 para que el batch se esté procesando en el tiempo t en k_j es $t - TL_{drk_j} + 1$. En consecuencia, resulta que un batch de la orden d asignada al camino r se esta procesando en el tiempo t en la unidad k_j, si y sólo si uno de los puntos del intervalo $[t - TL_{drk_j} + 1, t - TU_{drk_j}]$, los cuales están representados en la Figura 1 con círculos azules, es seleccionado para su inicio.

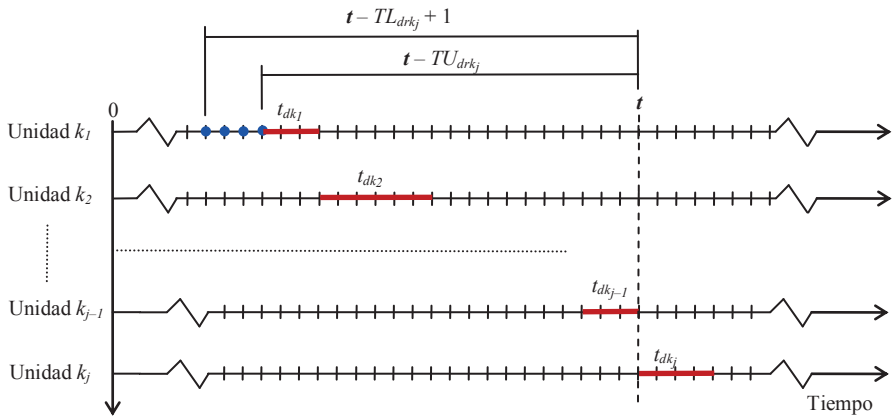

Fig. 1. Grillas de tiempos para el secuenciamiento en la unidad k_j de la etapa j

En general, un batch de la orden d asignada al camino r se estará procesando en el punto t de la grilla sobre la unidad k que forma parte del camino r si y sólo si su procesamiento se inicia en algún punto de tiempo t' con $t - TL_{drk} + 1 \leq t' \leq t - TU_{drk}$.

De esta manera, considerando todas las órdenes, batches posibles en los que se pueda particionar y caminos factibles para sus procesamientos, se puede asegurar que en el punto de tiempo t y en la unidad k no se estará procesando más de un batch si se satisface la siguiente restricción:

$$\sum_{d\in D}\sum_{n\in N_d}\sum_{b\in DB_{dn}}\sum_{\substack{r\in POS_{dnb}\\ r\in RK_k}}\sum_{t'=t-TL_{drk}+1}^{t-TU_{drk}} y_{dnbrt'} \leq 1 \qquad \forall j \in J, k \in KJ_j, t \in T \tag{5}$$

Con el fin de romper la simetría del problema y evitar soluciones redundantes se impone que si dos batches b, b' de la orden d, con $b < b'$, son asignados al mismo camino r entonces el tiempo de inicio de procesamiento de b es menor al de b', esto es

$$\sum_{\substack{t'\in TDR_{dr}\\ t'<t+t_{dk}}} y_{dnb+1rt'} = 1 - y_{dnbrt} \qquad \forall d \in D, n \in N_d, n \geq 2, b, b+1 \in DB_{dn}, \quad t \in TDR_{dr}, k \in KJ_1, r \in POS_{dnb}, r \in RK_k \tag{6}$$

3.4. Satisfacción de la demanda

Debe ser factible satisfacer la demanda de cada orden con el número de batches en que se divide y los caminos a los cuales se asignan, para que esto ocurra, debe satisfacerse la desigualdad

$$\sum_{n\in N_d}\sum_{b\in DB_{dn}}\sum_{r\in POS_{dnb}}\sum_{t\in TDR_{dr}} B_{dr}^{\min} y_{dnbrt} \leq Q_d \leq \sum_{n\in N_d}\sum_{b\in DB_{dn}}\sum_{r\in POS_{dnb}}\sum_{t\in TDR_{dr}} B_{dr}^{\max} y_{dnbrt} \qquad \forall d \in D \tag{7}$$

3.5. Función objetivo

El objetivo es minimizar el makespan (*MK*), es decir el máximo tiempo requerido para procesar todas las órdenes. La siguiente ecuación asegura que *MK* sea mayor o igual que cada uno de los tiempos finales de procesamiento

$$MK \geq (t + t_{dr})y_{dnbrt} \qquad \forall d \in D, n \in N_d, b \in DB_{dn}, r \in POS_{dnb}, t \in TDR_{dr} \tag{8}$$

luego, el modelo resulta

$$\text{Minimizar } MK \tag{9}$$

sujeto a las restricciones 1 a 8.

4 Ejemplo

En esta sección se presenta un ejemplo que permite mostrar tanto la capacidad para generar una solución para el problema como la performance computacional del modelo desarrollado en este trabajo. Se considera una planta batch de tres etapas, con dos unidades diferentes en cada una de ellas, operando en paralelo y fuera de fase. La estructura, como así también las capacidades máximas de las unidades, son conocidas, y se ilustran en la Figura 2.

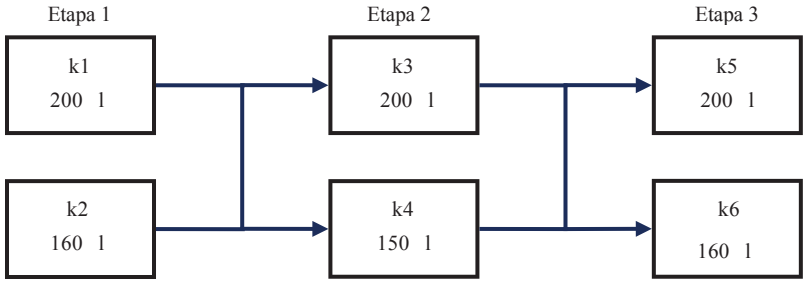

Fig. 2. Estructura de la planta

De acuerdo a la estructura de la planta, es posible definir 8 caminos diferentes. Para simplificar, en este ejemplo, se consideran los factores de tamaño iguales a uno para todas las órdenes y todas las etapas, mientras que el porcentaje mínimo de ocupación es del 70% en cada unidad. Teniendo en cuenta estas consideraciones, es posible determinar los tamaños mínimos y máximos admisibles para cada batch en cada camino, independientemente de la orden. Las unidades que componen cada camino como así también los tamaños mínimo y máximo en cada uno de ellos se muestran en la Tabla 1.

Tabla 1. Definición de los caminos y tamaños admisibles para los batches

Camino	Unidad de cada etapa que compone el camino			$B_r^{\min}$	$B_r^{\max}$
	Etapa 1	Etapa 2	Etapa 3		
r1	k1	k3	k5	140	200
r2	k1	k3	k6	140	160
r3	k1	k4	k5	140	150
r4	k1	k4	k6	140	150
r5	k2	k3	k5	140	160
r6	k2	k3	k6	140	160
r7	k2	k4	k5	140	150
r8	k2	k4	k6	112	150

La planta debe procesar un conjunto de doce órdenes {d1, d2,…, d12}, cuyas demandas, fechas de emisión y límite de entrega, y tiempos de procesamiento se presentan en la Tabla 2.

Tabla 2. Demandas, fecha de emisión y vencimiento y tiempos de procesamiento de las órdenes

Orden	Q_d (kg)	RD_d	DD_d	Tiempos de procesamiento t_{dk} (hs)					
				k1	k2	k3	k4	k5	k6
d1	380	0	30	3	4	3	4	4	5
d2	130	0	25	4	4	3	3	4	4
d3	225	0	25	5	4	5	4	6	5
d4	190	5	25	2	3	2	2	3	4
d5	340	5	40	3	3	3	4	3	4
d6	530	0	35	2	2	3	3	2	3
d7	430	0	35	5	4	5	4	5	4
d8	390	10	45	2	3	2	3	3	4
d9	300	10	50	4	3	3	5	5	4
d10	340	10	50	2	2	2	3	3	3
d11	290	15	45	5	4	5	4	5	4
d12	360	15	50	2	3	2	2	3	4

Tabla 3. Batching y scheduling óptimo de las órdenes

Orden	Batches	Camino	Tiempo de inicio (hs)	Tiempo final (hs)
d1	b1	r1	2	12
	b2	r1	6	16
d2	b1	r8	0	11
d3	b1	r8	4	17
	b2	r8	9	22
d4	b1	r1	18	25
d5	b1	r1	10	19
	b2	r5	13	22
d6	b1	r1	0	7
	b2	r1	23	30

	b3	r1	28	35
d7	b1	r4	13	26
	b2	r8	18	30
	b3	r8	22	34
d8	b1	r1	21	28
	b2	r1	31	38
d9	b1	r2	34	45
	b2	r8	37	49
d10	b1	r1	26	33
	b2	r6	34	41
d11	b1	r7	30	43
	b2	r8	26	38
d12	b1	r1	39	46
	b2	r1	42	49

Para la resolución del problema se propone una grilla de tiempos discretos desde 0 hasta 50 o sea, desde 0 hasta la mayor de las fechas de vencimiento, con paso $\Delta t = 1$ que es el máximo común divisor entre todos los tiempos de procesamiento.

El ejemplo fue implementado en GAMS versión 24.7.4 y resuelto empleando el solver CPLEX 12.6.3, con un procesador Intel Core i7, 2.7 GHz, 12 GB de RAM. El modelo consta de 5410 ecuaciones, 7308 variables discretas y 1 variable continua correspondiente al makespan. La obtención del óptimo global demandó un tiempo de CPU de 52 segundos.

En la solución óptima el makespan resulta ser 49 horas. En la Tabla 3 se resumen los resultados obtenidos, indicando los batches en que se divide cada orden, los caminos en que se procesa cada batch y los tiempos iniciales y finales de procesamiento de los mismos, a fin de satisfacer los requerimientos de demanda en el mínimo tiempo total de procesamiento. Como puede observarse, es necesario procesar 24 batches para satisfacer la demanda de las 12 órdenes. Las órdenes d6 y d7 debieron ser divididas en tres batches cada una, d2 y d4 pudieron ser completadas con un único batch, mientras que las restantes han sido satisfechas empleando dos batches. Cada orden satisface su fecha de emisión y límite de entrega.

En la Figura 3, se ilustra el diagrama de Gantt de la solución óptima.

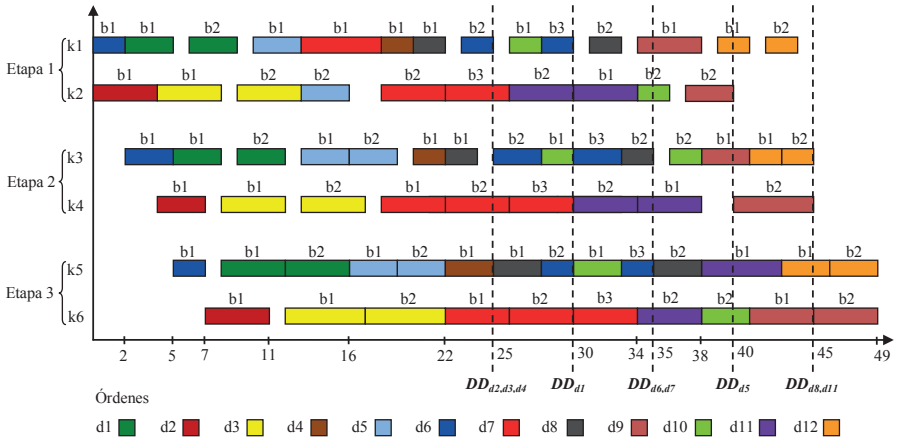

Fig. 3. Diagrama de Gantt de la solución óptima

5 Conclusiones

El modelo desarrollado en este trabajo permite resolver simultáneamente los problemas de batching y scheduling minimizando el tiempo total de procesamiento, proporcionando el número de batches en que se divide cada orden, las unidades en que se procesa cada batch y sus tiempos inicial y final de procesamiento. La nueva representación para decidir el procesamiento de las órdenes, basada en caminos de producción, y la definición de tiempos discretos, han demostrado ser computacionalmente eficiente, permitiendo resolver problemas de considerable tamaño en tiempos reducidos. De este modo, se proporciona una herramienta eficiente para optimizar la operación de una planta batch multiproducto.

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Flow-shop con consideraciones energéticas y aplicación de lot-streaming

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Abstract. La necesidad de generar programas de producción sustentables, ha contribuido a nuevos desarrollos innovadores en la gestión de operaciones. En muchos casos se han generado enfoques y herramientas que permitieron mejorar la sustentabilidad de las industrias. Dentro de esas mejoras, un tema recurrente, es la reducción del consumo energético y de las emisiones de carbono. En este trabajo se aborda el problema de scheduling de flow-shop con consideraciones energéticas utilizando estrategias de lot-streaming. Las estrategias de lot-streaming permiten dividir un trabajo (o lote de un mismo producto) en pequeños sublotes, de forma que esos sublotes puedan avanzar de etapa de producción, aun cuando parte del trabajo sigue procesándose en la etapa de producción anterior. El consumo energético se modela dentro de la función objetivo, junto con el makespan, por medio de una suma normalizada y ponderada. De esta forma, la reducción del consumo energético guía el proceso de optimización. Los experimentos evalúan el impacto de utilizar estrategias de lot-streaming en este tipo de problemas. Los resultados permitieron demostrar que el lot-streaming es una estrategia eficiente a la hora de resolver este problema, permitiendo mejorar tanto el makespan como el consumo energético total con respecto al problema sin lot-streaming. A su vez, se incorporó la selección de velocidades de procesamiento para cada sublote, lo que mejoró la estrategia.

Keywords: Scheduling, flow-shop, lot-streaming, operaciones sustentables.

1 Introducción

En las últimas décadas ha crecido la conciencia global sobre la necesidad de cambiar a sistemas industriales más sustentables [1]. Esto disminuiría los impactos negativos del

cambio climático reduciendo las emisiones de carbono [2]. Una de las formas más directa de reducir estas emisiones es disminuir el consumo energético, reduciendo así, la combustión de combustibles fósiles [3]. Dentro de la producción de productos manufacturados, la reducción del consumo energético puede abordarse desde tres perspectivas distintas [4] [5]:

1. A nivel de la maquinaria: se busca desarrollar máquinas más eficientes y que requieran menos cantidad de energía.

2. A nivel del producto: se busca diseñar un producto desde el punto de vista del ahorro energético. Esto no es muy factible en empresas medianas y pequeñas ya que requiere mucha inversión.

3. A nivel de la fábrica: se puede optar por un modelo de decisiones que soporten y contribuyan al ahorro energético.

Este trabajo se enmarca en esta última perspectiva, buscando desarrollar herramientas de apoyo a la toma de decisión que contribuyan al ahorro energético, puntualmente considerando problemas de scheduling. Incluir consideraciones energéticas en la resolución de problemas de scheduling mostró ser muy efectiva en la reducción energética, logrando reducciones de hasta el 80% [6]. Dentro de los primeros trabajos sobre esta línea resalta el trabajo de Mouzon et al. [3], en donde los autores desarrollaron un estudio de reglas de despacho, y luego un modelo multi-objetivo que permitió resolver el scheduling reduciendo considerablemente los consumos energéticos para máquinas del tipo CNC (Control Numérico de Computadoras). Un aspecto crítico a la hora de buscar reducir el consumo energético, es minimizar la potencia máxima consumida por el proceso productivo, ya que cuando se incrementa la potencia el consumo energético aumenta más que proporcionalmente (es decir, la proporcionalidad entre aumento de potencia entregada en el eje de la máquina y el aumento en el consumo energético es exponencial). Por lo que, buscar minimizar el pico máximo de consumo energético contribuye a la eficiencia energética, y en consecuencia a minimizar las emisiones de carbono [7]. Este enfoque de buscar minimizar el pico de consumo energético fue abordado por primera vez por Fang et al. [8]. En ese trabajo los autores desarrollaron modelos matemáticos multi-objetivos que buscaron minimizar el pico de consumo en un sistema flow-shop, el makespan y las emisiones de carbono. Esos modelos consideraron la velocidad de procesamiento de cada operación como una variable de decisión. Mientras que Fang et al. [9] profundizaron su estudio al considerar nuevamente sistemas flow-shop buscando minimizar el consumo energético, pero desarrollan formulaciones matemáticas fortalecidas, así como enfoques combinatorios que permitieron resolver el problema. A su vez, en ese trabajo, consideraron dos variantes de flow-shop, una sin almacenamiento intermedio entre etapas sucesivas (si no hay almacenamiento intermedio, una máquina no puede liberarse hasta que se libere la siguiente máquina), y otra variante con almacenamiento intermedio ilimitado. Bruzzone et al. [7] abordaron el problema de minimizar el pico de consumo energético, pero en sistemas flow-shop flexibles (más de una máquina en paralelo por etapa). En este trabajo, los autores, plantearon un enfoque de resolución basado en etapas, en donde primero resuelven el scheduling buscando minimizar una función objetivo tradicional como el makespan. Luego,

en una segunda etapa, reprogramar el inicio de las actividades. Por otro lado, Mansouri et al. [10] utilizaron un enfoque multi-objetivo para resolver un sistema flow-shop de 2 etapas. Los objetivos que consideraron los autores fueron el makespan y el consumo energético total, y resolvieron el problema utilizando el método de ε-restricciones.

Sin embargo, hasta donde se conoce, no se han utilizado estrategias de lot-streaming para el problema del flow-shop con consideraciones energéticas. Es por eso que en este trabajo se propone resolver el problema de flow-shop con consideraciones energéticas mediante estrategias de lot-streaming. El lot-streaming permite dividir los lotes de producción en sublotes, los cuales pueden avanzar de una estación de trabajo a otra sin esperar a que se procese el lote completo [11]. De esta forma se puede solapar la producción de un mismo lote en más de una etapa de producción, favoreciendo la eficiencia del sistema al reducir los tiempos de ciclos de producción [12]. Por otro lado, permite reducir los tiempos de makespan considerablemente para sistemas de flow-shop no-permutativos [13], así como lidiar de forma eficiente con sistemas complejos de flow-shop en donde una de las etapas de producción funciona en modo batch [14]. Este trabajo busca implementar el lot-streaming para resolver el scheduling en sistemas flow-shop con consideraciones energéticas. La intención es aprovechar la capacidad de flexibilizar los tiempos de procesamiento de cada lote de producción al poder subdividirlo, y de esta forma flexibilizar el scheduling para minimizar el consumo energético.

2 El problema y los modelos matemáticos

Dada la importancia de considerar el consumo energético dentro de los problemas de scheduling, en este apartado se propone formalmente la incorporación de procesos de lot-streaming al cálculo del schedule. Para ello se parte describiendo detalladamente el problema a estudiar, para luego presentar los modelos matemáticos.

2.1 Problema estudiado

El problema estudiado en este trabajo se enmarca dentro de la línea de scheduling con consideraciones energéticas [3]. En estos problemas se busca resolver el problema clásico de scheduling [15]: asignar los trabajos o tareas a los recursos disponibles buscando minimizar alguna función objetivo. Al incorporar las consideraciones energéticas, se busca minimizar el impacto ambiental que generan las operaciones de producción por dos vías, o minimizar el consumo energético total [6] o el pico máximo de consumo energético [8]. Este trabajo busca minimizar el consumo energético total. Esto tiene razón de ser en entornos en que la velocidad de procesamiento de las tareas es variable, y ligada a esa variabilidad de velocidad está el consumo energético [10]. Por lo tanto, las operaciones aquí consideradas no son tareas constantes, sino que pueden incorporarse como variables de decisión al problema, lo que permite aumentar la eficiencia del schedule obtenido (hay mayores grados de libertad), pero a su vez implica un incremento en la complejidad del mismo [4] [9].

Por otro lado, se propone la innovación de incluir estrategias de lot-streaming al problema. El lot-streaming consiste en la subdivisión de los lotes de producción en

sublotes, de forma que estos puedan avanzar de operación aun cuando el lote completo no ha terminado su procesamiento en la operación anterior [16]. De esta forma, es posible que dos máquinas sucesivas del flow-shop estén procesando el mismo trabajo o lote (dividido en sublotes) simultáneamente [11]. Incorporar lot-streaming al problema considerado en este trabajo permite aumentar la flexibilidad en el proceso de asignación de trabajos, logrando aprovechar las mejoras que reporta lot-streaming a la hora de estudiar el makespan dejando mayor margen para la minimización del consumo energético total.

2.2 Modelos matemáticos

En esta sección se presentan los tres modelos matemáticos estudiados. El primero es el caso más general, flow-shop con consideraciones energéticas (FSS+EA), luego se incorpora la primera aproximación de lot-streaming a ese problema (SBS+EA). Finalmente, se incorpora el lot-streaming a la consideración energética al permitir modificar la velocidad de procesamiento para cada sublote (SBSI+EA).

2.2.1 Flow-shop con consideraciones energéticas (FSS+EA)

El primer modelo presentado se trata del problema clásico de scheduling en flow-shop con consideraciones energéticas (FSS+EA). Este modelo busca secuenciar los trabajos cumpliendo con las condiciones de producción (es decir que se respeten todas las operaciones que deben realizarse en cada trabajo), pero también, definiendo la velocidad de procesamiento de cada operación. Por lo que, tanto el secuenciamiento como la selección de velocidades de procesamiento intervienen en el cálculo de la función objetivo que contempla el makespan y el consumo energético. Estos objetivos son abordados a través de una suma ponderada normalizada. Además, como característica realista del problema, se contemplaron tiempos de preparación y remoción para cada trabajo. El modelo matemático se presenta a continuación.

Índices:

M: máquinas; $k = 1, 2, \ldots, m$.

J: trabajos o lotes; $j = 1, 2, \ldots, n$.

V: velocidad de procesamiento; $l = 1, 2, 3$.

Parámetros:

G: valor positivo lo suficientemente grande.

m: número de máquinas.

n: número de trabajos o lotes.

U_j: cantidad de unidades de producto j a procesar (tamaño del lote de producto j).

$TS_{j,k}$: tiempo de setup del trabajo j en la máquina k.

$P_{j,k}$: carga de trabajo estándar de procesar una unidad de producto j en la máquina k [segundos].

$RT_{j,k}$: tiempo de liberar la máquina k luego de procesar una unidad o más del producto j (es independiente de la cantidad de unidades procesadas).

$Vl1_l$: factor de velocidad para la velocidad seleccionada l. Puede tomar los valores 1.2, 1 y 0.8.

$Vl2_l$: factor de conversión energética para la velocidad de procesamiento l. Toma los valores 1.5, 1, 0.6 para rápido, normal y lento, respectivamente.

MO_k: factor de conversión energético para el tiempo ocioso de la máquina k.

PM_k: potencia de la máquina k.

Variables:

$C_{j,k}$: tiempo en completar el trabajo j en la máquina k.

$X_{j,jj}$: variable binaria, es 1 si el trabajo j se procesa antes que el trabajo jj, 0 en otro caso ($j \neq jj$).

$Y_{j,k,l}$: variable binaria, es 1 si el trabajo j se procesa a la velocidad l en la máquina k, 0 en otro caso.

C_{max}: tiempo de completar el último trabajo o makespan. (Nota: C_{max}^{min} representa el valor mínimo posible de C_{max} para esa instancia, C_{max}^{max} representa el valor máximo posible de C_{max} para esa instancia, C'_{max} representa el valor actual de la solución obtenida)

TEC: consumo energético. (Nota: TEC^{min} representa el valor mínimo posible de TEC para esa instancia, TEC^{max} representa el valor máximo posible de TEC para esa instancia, TEC' representa el valor actual de la solución obtenida)

Formulación:

$$\text{Minimizar } Z = 0.5 * \left(\frac{C'_{max} - C_{max}^{min}}{C_{max}^{max} - C_{max}^{min}}\right) + 0.5 * \left(\frac{TEC' - TEC^{min}}{TEC^{max} - TEC^{min}}\right) \quad (1)$$

Desglose de Z (ecuación 1):

$$C'_{max} \geq C_{j,k} + RT_{j,k}, \forall j, k = m \quad (2)$$

$$TO_k = C_{max} - \sum_j \sum_l \frac{P_{j,k} * U_j}{Vl1_l} * Y_{j,k,l}, \forall\, k \quad (3)$$

$$TEC' = \sum_k \sum_j \sum_l \frac{PM_k * P_{j,k} * U_j * Vl2_l}{60 * Vl1_l} * Y_{j,k,l} + \sum_k \frac{MO_k * PM_k}{60} * TO_k \quad (4)$$

Sujeto a:

$$C_{j,k} \geq \frac{P_{j,k} * U_j}{Vl1_l} * Y_{j,k,l} + TS_{j,k}, \forall j, k = 1 \quad (5)$$

$$C_{j,k} \geq C_{j,k-1} + \frac{P_{j,k} * U_j}{Vl1_l} * Y_{j,k,l} + RT_{j,k-1} + TS_{j,k}, k > 1, \forall j \quad (6)$$

$$C_{jj,k} \geq C_{j,k} + \frac{P_{jj,k} * U_{jj}}{Vl1_l} * Y_{jj,l,k} - G * \left(1 - X_{j,jj}\right) + RT_{j,k} + TS_{jj,k}, \forall k, jj \neq j \quad (7)$$

$$X_{j,jj} + X_{jj,j} = 1, jj \neq j \quad (8)$$

$$\sum_l Y_{j,k,l} = 1, \forall\, j, k \quad (9)$$

La función objetivo *Z* se presenta en la ecuación (1), en donde se muestra que la misma se compone por el makespan (C_{max}) y el consumo energético (*TEC*). También, en la ecuación (1), se muestra cómo es la normalización de *Z* para cada uno de los términos, y también las ponderaciones consideradas para este trabajo de 0.5. El cálculo de C_{max} se realiza según la ecuación (2). En la ecuación (3) se calcula el tiempo ocioso TO_k. Y en la ecuación (4) se obtiene el consumo energético, considerando las velocidades seleccionadas para procesar cada trabajo, así como el consumo durante el tiempo ocioso afectado por un factor de 60 segundos. Luego, se presentan las restricciones en las ecuaciones (5) - (9). La restricción (5) secuencia los trabajos para la primera máquina. En la restricción (6) se asegura que cada trabajo respete sus condiciones de precedencia entre operaciones. La restricción (7) secuencia los distintos trabajos, si el trabajo *j* se procesa antes que el trabajo *jj* para la máquina *k*, entonces se mantiene ese orden para todas las máquinas. La restricción (8) asegura que el ordenamiento inverso (*jj* antes de *j*) no sea válido. Por último, la restricción (9) asegura que para cada operación se seleccione una única velocidad.

2.2.2 Flow-shop con lot-streaming y consideraciones energéticas (SBS+EA)

Tomando como base el modelo FSS+EA, se incorpora al mismo la estrategia de lot-streaming dentro del proceso de scheduling. En este modelo cada trabajo *j*, compuesto por U_j unidades es dividido en *f* sublotes de tamaño $s_{i,j}$. Al considerar sublotes, también es necesario considerar que se empiezan a multiplicar los tiempos de traslado, ya que no ocurre una única vez para todo el lote U_j sino *f* veces (una para cada $s_{i,j}$). Por otro lado, al incorporar lot-streaming se multiplica la cantidad de veces que deben cargarse y descargarse las máquinas (una por cada sublote, en lugar de una para todo el lote), así como los tiempos de traslados o transferencias de las piezas. A continuación, se presenta sólo los índices y parámetros que se ven afectados por esta incorporación.

Índices:

I: sublotes: $i = 1, 2, \ldots, f$.

Parámetros:

f: número de sublotes.

$s_{i,j}$: tamaño del sublote *i* del producto *j* (cantidad de unidades contenidas en el sublote).

FT_j: tiempo fijo de transferencia del trabajo *j* (aplica para cada sublote sin depender de la cantidad de unidades contenidas en el mismo).

$RT_{j,k}$: tiempo de descarga asociada a la máquina *m* después de procesar un sublote del producto *j* en la máquina *k*.

Variables:

$C_{i,j,k}$: tiempo en completar el sublote *i* del trabajo *j* en la máquina *k*.

Desglose de Z (ecuación 1):

$$C'_{max} \geq C_{i,j,k} + RT_{j,k}, \forall\, j, k = m, i = f \tag{10}$$

$$TO_k = C_{max} - \sum_j \sum_i \sum_l \frac{p_{j,k}}{Vl1_l} * s_{i,j} * Y_{j,l,k}\,, \forall\, k \tag{11}$$

$$TEC' = \sum_k \sum_j \sum_i \sum_l \frac{PM_k * P_{j,k} * s_{i,j} * Vl2_l}{60 * Vl1_l} * Y_{j,l,k} + \sum_k \frac{MO_k * PM_k}{60} * TO_k \tag{12}$$

Sujeto a:

$$C_{i,j,k+1} - \frac{p_{j,k+1}}{Vl1_l} * s_{i,j} * Y_{j,k,l} \geq\ C_{i,j,k} + TS_{j,k+1} + FT_j, \forall\, j, k < m, i = 1 \tag{13}$$

$$C_{i,j,k+1} - \frac{p_{j,k+1}}{Vl1_l} * s_{i,j} * Y_{j,k,l} \geq\ C_{i,j,k} + FT_j, \forall\, j, i > 1, k < m \tag{14}$$

$$C_{i,j,k} - \frac{p_{j,k}}{Vl1_l} *\ s_{i,j} * Y_{j,k,l} \geq TS_{j,k}, \forall\, j, i = 1, k = 1 \tag{15}$$

$$C_{i,j,k} - \frac{p_{j,k}}{Vl1_l} *\ s_{i,j} * Y_{j,k,l} \geq C_{i-1,j,k}, \forall\, j, k, i > 1 \tag{16}$$

$$C_{ii,jj,k} - \frac{p_{jj,k}}{Vl1_l} * s_{ii,jj} * Y_{jj,k,l} - TS_{jj,k} + G * \left(1 - X_{j,jj}\right) \geq C_{i,j,k} + RT_{j,k}, \forall\, j, jj, k, ii = 1, i = I, j \neq jj \tag{17}$$

El cálculo de C_{max} ahora considera la finalización del último sublote procesado en la última máquina *m* (ecuación 10). También el tiempo ocioso se modifica (ecuación 11), ya que las operaciones son dependientes del tamaño del sublote $s_{i,j}$. Lo mismo para el total de energía consumida (ecuación 12). Al incorporar el lot-streaming se modifican algunas restricciones del problema. En la restricción (13) se secuencia el primer sublote del trabajo *j*, y se contemplan los tiempos de traslado entre dos máquinas consecutivas. En la restricción (14) se verifica que cada sublote respete la precedencia de operaciones del flow-shop. En la restricción (15) se cumple con la capacidad requerida en la primera máquina por el primer sublote. El ordenamiento de los sublotes de un mismo trabajo *j* se obtiene por la restricción (16). Sin embargo, al no permitir entremezcla, el secuenciamiento entre trabajos se realiza por la misma variable que en el modelo anterior, aunque en este caso la restricción (17) incorpora la proporcionalidad de los procesamientos según $s_{i,j}$.

2.2.3 Flow-shop con lot-streaming, velocidad indexada en los sublotes y consideraciones energéticas (SBSI+EA)

En este modelo, además de incluir la estrategia de lot-streaming como división de lotes de producción, también se lo incorpora en la decisión sobre la velocidad de procesamiento (SBSI+EA). Tomando como base el modelo SBS+EA, se incorpora una nueva variable para definir las velocidades de procesamiento.

Variables:

$Y_{i,j,k,l}$: variable binaria, es 1 si el sublote *i* del trabajo *j* se procesa a la velocidad *l* en la máquina *k*, 0 en otro caso.

Desglose de Z (ecuación 1):

$$TO_k = C_{max} - \sum_j \sum_i \sum_l \frac{p_{j,k}}{Vl1_l} * s_{i,j} * Y_{i,j,l,k}, \forall\, k \tag{18}$$

$$TEC' = \sum_k \sum_j \sum_i \sum_l \frac{PM_k * p_{j,k} * s_{i,j} * Vl2_l}{60 * Vl1_l} * Y_{i,j,l,k} + \sum_k \frac{MO_k * PM_k}{60} * TO_k \tag{19}$$

Sujeto a:

$$C_{i,j,k+1} - \frac{p_{j,k+1}}{Vl1_l} * s_{i,j} * Y_{i,j,k,l} \geq C_{i,j,k} + TS_{j,k+1} + FT_j, \forall\, j, k < m, i = 1 \tag{20}$$

$$C_{i,j,k+1} - \frac{p_{j,k+1}}{Vl1_l} * s_{i,j} * Y_{i,j,k,l} \geq C_{i,j,k} + FT_j, \forall\, j, i > 1, k < m \tag{21}$$

$$C_{i,j,k} - \frac{p_{j,k}}{Vl1_l} * s_{i,j} * Y_{i,j,k,l} \geq TS_{j,k}, \forall\, j, i = 1, k = 1 \tag{22}$$

$$C_{i,j,k} - \frac{p_{j,k}}{Vl1_l} * \ s_{i,j} * Y_{i,j,k,l} \geq C_{i-1,j,k}, \forall\, j,k,i > 1 \tag{23}$$

$$C_{ii,jj,k} - \frac{p_{jj,k}}{Vl1_l} * s_{ii,jj} * Y_{ii,jj,k,l} - TS_{jj,k} + G * \left(1 - X_{j,jj}\right) \geq C_{i,j,k} + RT_{j,k}\ , \forall\, j, jj, k, ii = 1, i = I, j \neq jj \tag{24}$$

$$\sum_{l} Y_{i,j,k,l} = 1, \forall\, j,k \tag{25}$$

El tiempo ocioso TO_k se modifica (ecuación 18), al incorporar la variable $Y_{i,j,k,l}$. Lo mismo ocurre con el consumo energético (*TEC*) (ecuación 19). Luego, las restricciones (20) - (25) tienen una interpretación similar a la del modelo SBS+EA, con la diferencia de que ahora la duración de los procesamientos se puede modificar para cada sublote *i* de cada trabajo *j*. Este último modelo, naturalmente, incluye un aumento en la cantidad de las variables binarias, lo que dificulta su resolución.

3 Experimentación

El diseño experimental busca comparar los modelos y mostrar empíricamente si la incorporación de lot-streaming es ventajosa a la hora de abordar problemas de scheduling en flow-shop con consideraciones energéticas. Para ello, se tomaron como punto de partida los trabajos que han utilizados enfoques similares [7] [10]. Respecto a la parametrización relacionada al lot-streaming se siguió a Rossit et al. [13] y Ferraro et al. [14]. Los tamaños de los problemas estudiados consideraron 5 y 10 máquinas, y se utilizaron 3, 5 y 7 trabajos para cada cantidad de máquinas. Por otro lado, para los parámetros definidos en la sección 2.1 para los distintos modelos se utilizó la siguiente parametrización:

U_j: aleatorio uniforme entre [4;24]*5. Entonces, los lotes de cada trabajo *j* quedan entre 20 y 120 como en [10].

$s_{i,j}$: se calcula dividiendo el valor de U_j entre los 5 sublotes para cada conjunto de datos.

$TS_{j,k}$: aleatorio uniforme entre [1;25].

$P_{j,k}$: aleatorio uniforme entre [1;5] ya que es tiempo unitario para unidad del lote U_j.

FT_j: aleatorio uniforme entre [1;4].

$RT_{j,k}$: aleatorio uniforme entre [2;6].

$Vl1_l$: toma algunos de los tres valores siguientes (1.2, 1, 0.8). Este factor se aplica al $P_{j,k}$, por lo que puede hacer en tiempo estándar (1), más rápido (1.2) o más lento (0.8).

$Vl2_l$: toma algunos de los tres valores siguientes (1.5, 1, 0.6). Dependiendo del valor de $Vl1_l$ seleccionado respectivamente.

MO_k: 0.05.

PM_k: 60 KW.

Para cada tamaño del problema se generaron 5 conjuntos de datos. Cada uno de estos conjuntos de datos fue resuelto por los tres modelos. Las experimentaciones se realizaron en una computadora AMD A6-7310 APU with AMD Radeon R4 Graphics con 8gb de RAM. Todos los modelos fueron implementados en Pyomo [17] y como solver se utilizó GUROBI 8.1.1. Para el post procesamiento de datos se utilizó SolverStudio [18].

4 Comparación de resultados

En la tabla 1 se muestran los valores promedios obtenidos para cada problema considerando cada uno de los modelos (FSS+EA, SBS+EA y SBSI+EA). Los resultados se expresaron según los términos, C_{max} y *TEC*. En la tabla, se puede observar que en todos los casos los modelos que consideran lot-streaming (SBS+EA y SBSI+EA) superan al modelo que no lo considera (FSS+EA), tanto en el C_{max} como en el *TEC*. En términos de C_{max} estas diferencias son muy notorias, ya que por ejemplo para el problema 5J-5M, el modelo FSS+EA obtiene un C_{max} promedio de 2173, mientras que el modelo SBS+EA lo reduce a 1472, y el modelo SBSI+EA lo lleva a 1462. Esta tendencia se mantiene para todos los problemas. Por el lado del *TEC*, se observa el mismo comportamiento, el modelo FSS+EA es el de peor desempeño, mientras que SBS+EA mejora sobre FSS+EA, y el mejor de los tres modelos es el SBSI+EA.

Tabla 1. Valores promedio obtenidos realizando 5 corridas por modelo y por instancia.

Problemas	C_{max}			*TEC*		
	FSS+EA	**SBS+EA**	**SBSI+EA**	**FSS+EA**	**SBS+EA**	**SBSI+EA**
3J-5M	1988	1170	1154	4522	4055	3865
3J-10M	2940	1367	1323	7984	6676	6534
5J-5M	2173	1472	1462	6007	5753	5420
5J-10M	3461	1785	1746	11267	10056	9724
7J-5M	2302	1510	1508	6349	6014	5648
7J-10M	3642	2095	2080	13218	12036	11562

Para analizar mejor los beneficios que reporta la incorporación del subloteo sobre este problema se presenta la tabla 2. En esta tabla, se muestran las diferencias porcentuales de mejora para C_{max} y *TEC*, tomando como base el resultado obtenido por el modelo FSS+EA. La tabla permite dimensionar mejor el impacto de lot-streaming sobre el problema de flow-shop con consideraciones energéticas. Ya que, en términos de makespan, en todos los casos las mejoras de los modelos SBS+EA y SBSI+EA sobre el FSS+EA superan al 30% de reducción, incluso llegando a mejoras por encima del 50% para el problema 3J-10M. Estos resultados condicen con los mostrados en la literatura de lot-streaming, en donde al permitir solapar actividades es posible reducir el makespan.

Tabla 2. Porcentaje de mejora de los modelos SBS+EA y SBSI+EA con respecto a FSS+EA.

Problemas	C_{max}		*TEC*	
	SBS+EA	**SBSI+EA**	**SBS+EA**	**SBSI+EA**
3J-5M	41,20%	42,00%	10,30%	14,50%
3J-10M	53,50%	55,00%	16,40%	18,20%
5J-5M	32,30%	32,70%	4,20%	9,80%
5J-10M	48,40%	49,50%	10,70%	13,70%
7J-5M	34,40%	34,50%	5,30%	11,00%
7J-10M	42,50%	42,90%	8,90%	12,50%

Sin embargo, los resultados relativos al *TEC* son también alentadores, ya que lot-streaming permite reducir el consumo energético de forma simultánea junto con el makespan. A su vez, estas reducciones del *TEC* también son significativas, alcanzando valores por encima del 16% para el SBS+EA y del 18% para el SBSI+EA para el problema 3J-10M. La reducción mínima que alcanza el lot-streaming es del 4% (SBS+EA) para el problema 5J-5M, lo que sigue siendo un valor representativo, ya que la implementación de lot-streaming no implica una inversión en capital para mejorar la capacidad instalada. Mientras que reducir el consumo energético, sí constituye una reducción directa en los costos.

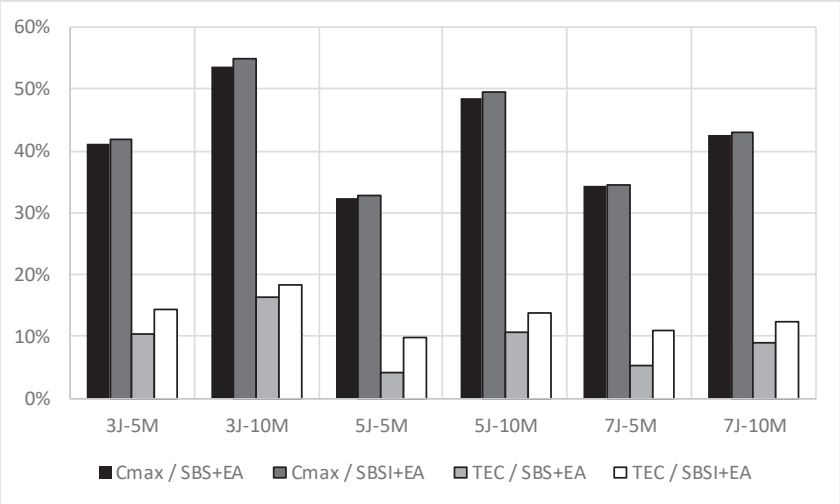

Fig. 1. Porcentaje de mejora de los modelos SBS+EA y SBSI+EA con respecto a FSS+EA.

Finalmente, para visualizar mejor el comportamiento de los modelos que consideraron lot-streaming sobre el flow-shop clásico, se presenta la figura 1. En ella se observan gráficamente los valores de la tabla 2. Se pueden apreciar los beneficios que traen la

incorporación de lot-streaming, así como los beneficios de permitir la selección de velocidad de procesamiento según el sublote. Respecto a incorporar lot-streaming es clara la ventaja tal como se comentó anteriormente, siendo el impacto en términos porcentuales, mucho más pronunciado para el makespan que para el consumo energético. Por otro lado, es posible ver que considerar la selección de la velocidad de procesamiento según el sublote (SBSI+EA), no mejora significativamente el makespan sobre no hacerlo (SBS+EA). Mientras que para el consumo energético si lo logra hacer.

Por otro lado, en la Tabla 3 se presentan los resultados sobre las velocidades, en promedio, más veces seleccionadas para tamaño de problema. Lo que se observa en la Tabla 3 es que, en términos generales, la velocidad más veces seleccionada es la 3, es decir, la velocidad de procesamiento más lenta. Sólo hay algunas excepciones para el modelo FSS+EA, es decir el que no utiliza sublotes. Mientras que para los modelos que se permiten los sublotes, la velocidad 3 es casi la selección unánime. Naturalmente, lo que se puede inferir a partir de estos resultados es que lot-streaming permite reducir el makespan de forma significativa. Ya que para el caso en que no se puede dividir la producción en sublotes (FSS+EA), hay alternancias entre la velocidad 1 (la más rápida, por ende, la que mejor makespan arroja, pero la que más consumo energético demanda), y la velocidad 3 (la que peor makespan permite, pero mejor consumo energético demanda). Sin embargo, cuando se puede dividir la producción en sublotes, como en los casos SBS+EA y SBSI+EA, la velocidad 3 es la que más veces se obtiene. Es decir, que lot-streaming permite reducir el makespan y el sistema puede abocarse a minimizar el consumo energético. No obstante, estos comentarios no son concluyentes.

Tabla 3. Valores promedio de las velocidades seleccionadas para los modelos: 1 = velocidad más rápida, 2 = velocidad intermedia y 3 = velocidad más lenta.

Problemas	FSS+EA	SBS+EA	SBSI+EA
3J 5M	1	3	3
3J 10M	3	3	3
5J 5M	3	1;3 (igual cantidad de veces)	3
5J 10M	1	3	3
7J 5M	3	3	3
7J 10M	1	3	3

En la Tabla 4, se presentan los tiempos de procesamiento que demandaron en promedio cada modelo para resolver los distintos problemas. Estos tiempos están medidos en segundos, y se consideró como tiempo límite 3.600 segundos. En los casos en que alcanzó el tiempo límite, se registró el GAP que registró el solver. De los datos mostrados en la Tabla 4, se observa el impacto computacional que tiene el lot-streaming. Ya que ambos modelos SBS+EA y SBSI+EA tienen tiempos de CPU ampliamente superiores a los del modelo FSS+EA. Incluso, el modelo SBSI+EA, que incorpora la decisión de la selección de velocidad de procesamiento a nivel del sublote, alcanza el límite de los 3.600 segundos a partir de los 5J y 10M.

Tabla 4. Valores promedio de los tiempos de procesamiento medidos en segundos. El tiempo límite es 3600 segundos. En paréntesis el GAP alcanzado el tiempo límite.

Problemas	FSS+EA	SBS+EA	SBSI+EA
3J 5M	< 1	2	795
3J 10M	1	8	2944
5J 5M	8	38	2939
5J 10M	28	1332	3600 (9,04%)
7J 5M	1806	2629	3600 (27,83%)
7J 10M	2574	3600 (6,69%)	3600 (16,86 %)

5 Conclusiones

En este trabajo se abordó un problema de scheduling en sistemas flow-shop con consideraciones energéticas. Este problema, de relevancia creciente en los últimos años, fue abordado con estrategias de lot-streaming, lo cual permite fraccionar el lote de trabajo de forma tal que se puedan solapar las actividades. Esta estrategia permite explotar la eficiencia de los sistemas productivos. En este trabajo, se la implementó con éxito. Se logró reducir de forma simultánea tanto el makespan como el consumo energético. Las reducciones logradas son más que significativas considerando que se trata únicamente de una estrategia de secuenciamiento, que no implica una inversión en capital para mejorar la capacidad instalada. Además, se comprobó que permitir variar la velocidad de procesamiento para cada sublote procesado profundizaba los beneficios en términos de consumo energético. No obstante, esta última opción trae aparejado un fuerte incremento en el costo computacional, por lo que a futuro se propone trabajar en métodos más eficiente de cálculo, como diseño de métodos heurísticos.

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Formulação indexada no tempo e algoritmo heurístico para um problema integrado de localização e sequenciamento

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Resumo Este trabalho lida com um problema integrado de localização de facilidades e sequenciamento da produção. O problema consiste na escolha de onde localizar p máquinas, dentre um conjunto finito de possibilidades e em sequenciar um conjunto de tarefas nessas máquinas de modo a minimizar o *makespan*. Cada tarefa possui uma *release date* dependente da localização e um tempo de processamento. Dessa forma, as decisões associadas com a localização das máquinas têm um impacto direto nas decisões do sequenciamento da produção, justificando a resolução integrada dos problemas. Para resolver este problema integrado, uma formulação matemática indexada no tempo e um algoritmo de busca local iterada são propostos. Os algoritmos foram avaliados e comparados com métodos propostos na literatura através de experimentos computacionais. Os resultados obtidos mostram que os métodos propostos apresentam desempenho melhores que os métodos da literatura, sendo capazes de achar soluções ótimas para 1399 das 1450 instâncias testadas.

Keywords: sequenciamento da produção, localização de facilidades, formulação indexada no tempo, busca local iterada, makespan

1 Introdução

Problemas de localização de facilidades e sequenciamento de tarefas são problemas bastante estudados na área de otimização combinatória. A principal motivação para estudá-los vem da possibilidade de aplicação em diversos contextos (como logística, gestão de projetos, planejamento da produção, processamento de dados, etc.), bem como do desafio em gerar soluções eficientes, pois muitos deles pertencem a classe de problemas NP-Difícil ([2, 12, 17, 18]). Desde a década de 60 muitos artigos científicos foram publicados nestes temas, porém poucos deles abordaram os problemas de maneira integrada.

Neste contexto, o problema *ScheLoc* combina o sequenciamento de tarefas com a localização de facilidades em um único e integrado problema. O *ScheLoc*

consiste em selecionar os locais de p máquinas e em sequenciar um conjunto de tarefas a serem processadas nestas máquinas. Para processar uma tarefa, a mesma deve ser transportada (e.g., de um armazém ou fornecedor externo) para o local da máquina que irá processá-la. O tempo necessário para realizar este transporte define o tempo mais cedo que as tarefas estarão disponíveis para serem processadas em cada máquina (ou local). Possíveis aplicações do problema de *ScheLoc* incluem, e.g., a utilização de máquinas móveis cujo o posicionamento pode variar de acordo com o objetivo do sequenciamento, a localização de trituradores para processamento de minerais, a escolha do melhor posição para atracar um navio a ser carregado e a localização de dispositivos de treinamento para forças militares ([3, 5–8]).

O foco deste artigo está no estudo de uma variante do *ScheLoc* em que i) os locais candidatos para localização das p máquinas está restrito à um conjunto discreto, ii) as máquinas são consideradas idênticas e operam em paralelo, e iii) o objetivo consiste na minimização do makespan (i.e., tempo de término da última tarefa). Este problema é conhecido na literatura por *discrete parallel machine makespan ScheLoc problem* (DPMMSP). Para solucionar o problema, uma nova formulação matemática (indexada no tempo) e um algoritmo baseado na metaheurística de busca local iterada são propostos. Experimentos computacionais são realizados em um conjunto de 1450 instâncias da literatura e diversas soluções ótimas são encontradas pela primeira vez.

O restante do trabalho está organizado da seguinte maneira. A Seção 2 apresenta uma breve revisão da literatura. Uma descrição formal do DPMMSP bem como a formulação proposta são apresentadas na Seção 3. O algoritmo heurístico é detalhado na Seção 4. Os experimentos computacionais e os resultados obtidos são reportados na Seção 5. Por fim, as conclusões e sugestões de trabalhos futuros são apresentados na Seção 6.

2 Revisão da literatura

O *ScheLoc* foi introduzido na literatura em [5] com o objetivo de minimizar o *makespan*. Nesta primeira versão, os autores consideraram apenas uma máquina que poderia ser localizada em qualquer lugar em uma rede (i.e., em nós ou arestas). Kaufmann [9] também estudou o problema de *ScheLoc* para uma única máquina, porém considerando diferentes funções objetivos. Kalsch e Drezner [8], por outro lado, estudaram a versão em que uma única máquina poderia ser localizada em qualquer local de um plano do $\mathbb{R}^2$ para minimizar o *makespan* ou o tempo total de término das tarefas. Vale frisar que, uma vez que o local da máquina esteja definido, a resolução dos problemas de *ScheLoc* mencionados se reduzem ao problema de sequenciamento de uma única máquina com *release dates* $(1|r_j|C_{\max})$, que pode ser resolvido na otimalidade em tempo polinomial com por meio da regra do *earliest release date* (ERD) ([1, 13, 18]).

O DPMMSP foi proposto por Hessler e Deghdak [6] e difere das versões anteriores ao considerar p máquinas paralelas cujas localizações devem ser selecionadas de um conjunto discreto de locais candidatos. Além das decisões de

localização, o DPMMSP envolve a alocação de tarefas à locais (ou máquinas) e o sequenciamento de tarefas em p máquinas. Para resolver o problema, os autores propuseram uma formulação matemática, procedimentos para obtenção de *lower bounds* e algumas heurísticas baseadas em algoritmos de clusterização combinadas com procedimentos de busca local baseada na regra do ERD. Mais recentemente, Wang *et al.* [21] apresentaram uma formulação de fluxo em redes e três procedimentos heurísticos para solucionar o DPMMSP. Baseado em experimentos computacionais, os autores mostraram que dentro de um tempo limite de uma hora a formulação proposta é capaz de resolver mais instâncias que a formulação apresentada em [6], porém limitados à instância com menos de 20 tarefas. No tocante às soluções heurísticas, os resultados também são melhores que os reportados em [6], mas os *gaps* percentuais para os melhores *lower bounds* ainda são considerados grandes (cerca de 9% na média).

Uma versão similar ao DPMMSP foi estudada em [14], porém considerando máquinas paralelas não relacionadas. Um algoritmo mémetico baseado em busca tabu foi proposto para resolver o problema de maneira integrada. Moutrou-se, por meio de experimentos computacionais, que a abordagem integradas apresentava resultados melhores que uma abordagem sequencial (i.e., que resolver os problemas de localização e sequenciamento um após o outro, de maneira independente). Além disso, os autores resolveram instâncias do DPMMSP e os resultados obtidos foram melhores que os reportados por [6].

Outros trabalhos interessantes que merecem ser mencionados incluem o estudo de caso de [10] em uma indústria têxtil belga – onde são consideradas a possibilidade de múltiplas máquinas em um mesmo local (com locais já definidos) e, não só *release dates*, como também *due dates* – e os trabalhos de [15] e [11] que consideram incertezas nos tempos de processamento das tarefas.

3 Descrição do problema

O DPMMSP considera um conjunto $J = \{1, \ldots, n\}$ de tarefas a serem sequenciadas em no máximo p máquinas idênticas (em paralelo), cujas localizações devem ser escolhidas de um conjunto discreto $M = \{1, \ldots, m\}$ de locais candidatos (com $p < m$). Cada tarefa $j \in J$ tem que ser processada por p_j unidades de tempo por uma das p máquinas, sem interrupção, e apenas uma máquina pode ser localizada em um local candidato de M. Além disso, uma tarefa j só pode ser processada em um local k a partir de um determinado tempo r_{jk} (i.e., *release date*) que representa, por exemplo, o tempo associado ao transporte da matéria-prima necessária para executar a tarefa até o local do processamento. Os conjuntos J e M e os valores de p, p_j ($\forall j \in J$) e r_{jk} ($\forall j \in J$, $\forall k \in M$ são dados do problema. O objetivo consiste em minimizar o *makespan*, i.e., o tempo de término de processamento da última tarefa. O DPMMSP é um problema NP-Difícil pois generaliza o problema de sequenciamento em máquinas paralelas que é NP-Difícil ([4]). Um exemplo ilustrativo de uma instância com $m = 3$, $n = 6$ e $p = 2$ e uma possível solução são apresentadas na Figura 1, onde as duas máquinas são alocadas aos locais 1 e 3; as tarefas 5, 1 e 6 são processadas

no local 1; e as tarefas 4, 3 e 2 são processadas no local 3. Os tempos de início de cada tarefa são mostrados no gráfico de Gantt na parte inferior.

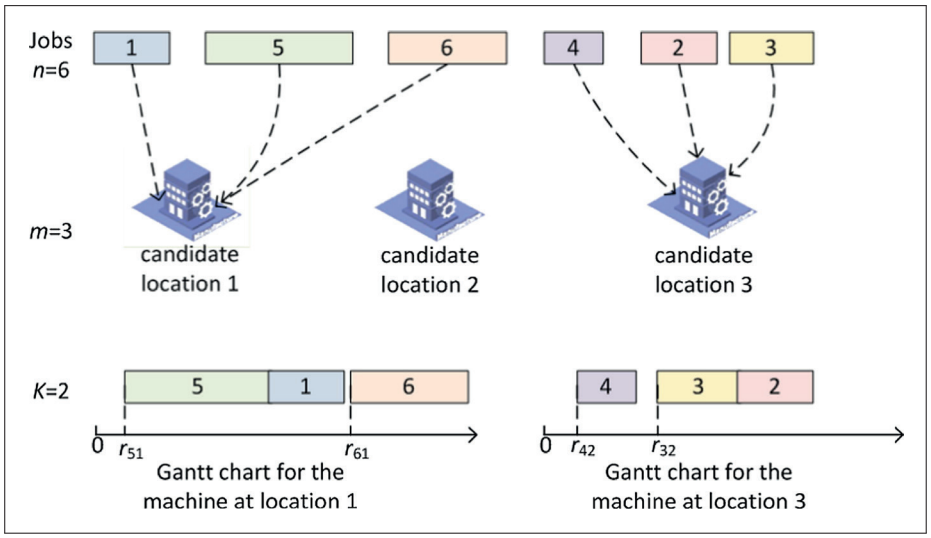


Figura 1: Exemplo gráfico de uma instância do DPMMSP e uma possível solução. Fonte: [21].

3.1 Formulação indexada no tempo

Nesta seção, apresentamos uma formulação baseada em programação inteira mista para o DPMMSP. A formulação proposta é uma adaptação da formulação indexada no tempo (TI, do inglês *Time-Indexed*) originalmente proposta por [19] para o problema de sequenciamento em uma máquina sujeito a restrições quanto à disponibilidade de recursos. Inicialmente, seja $H = \{0, 1, \ldots, T\}$ o conjunto discretizado de tempos, onde T é um limite superior para o tempo de término da última tarefa (i.e., *makespan*). Para modelar o DPMMSP por meio de uma formulação TI, considere a variável binária x_{jkt} que assume valor 1 se a tarefa $j \in J$ é processada por uma máquina localizada na localidade $k \in K$ e começa a ser processada no tempo $t \in H$, caso contrário assume o valor 0. Considere ainda a variável binária $y_k, k \in M$, que assume o valor 1 se a localidade k é selecionada para a instalação de uma máquina, ou 0 caso contrário; e a variável contínua $C_{\max}$ que representa o *makespan*. Considerando essas definições, a formulação TI para o DPMMSP é definida como se segue:

$$\text{(TI)} \quad \min \quad C_{\max} \tag{1}$$

s.a.

$$\sum_{k\in M}\sum_{t\in H} x_{jkt} \geq 1 \qquad j \in J, \tag{2}$$

$$\sum_{j\in J}\sum_{s=\max\{r_{jk};t-p_j+1\}}^{\min\{t;T-p_j\}} x_{jks} \leq y_k \qquad k \in M, t \in H, \tag{3}$$

$$\sum_{k\in M}\sum_{t\in H}(t+p_j)\, x_{jkt} \leq C_{\max} \qquad j \in J, \tag{4}$$

$$\sum_{k\in M} y_k \leq p, \tag{5}$$

$$C_{\max} \leq T, \tag{6}$$

$$y_k \in \{0,1\} \qquad k \in M, \tag{7}$$

$$x_{jkt} \in \{0,1\} \qquad j \in J, k \in M, t \in \{r_{jk}, ..., T-p_j\}. \tag{8}$$

A função objetivo (1) busca a minimização do *makespan*. As Restrições (2) forçam que cada tarefa $j \in J$ seja processada ao menos uma vez. As Restrições (3), por sua vez, garantem que as tarefas sejam processadas apenas nas localidades selecionadas, ou seja, naquelas em que existam máquinas instaladas, e que essas máquinas não processem mais de uma tarefa ao mesmo tempo. As Restrições (4) dizem que o *makespan* deve ser maior ou igual aos tempos de término de todas as tarefas, enquanto a Restrição (5) indica que no máximo p localidades devem ser escolhidas. Por fim, as Restrições (6)–(8) se referem ao domínio das variáveis.

4 Algoritmo heurístico

O algoritmo desenvolvido para solucionar o DPMMSP apresentado na Seção 3 se baseia na metaheurística de busca local iterada (ILS, do inglês *Iterated Local Search*). A ILS já foi utilizada para resolver com sucesso diversos problemas de otimização, incluindo os problemas de sequenciamento e de localização de facilidades ([16]).

A ILS é composta de quatro componentes principais: i) um método construtivo para gerar a solução inicial; ii) um procedimento de busca local para explorar soluções vizinhas; iii) um mecanismo de perturbação que permite escapar de ótimos locais e favorece a busca por ótimos locais em outras regiões do espaço de busca; e iv) um critério de aceitação que decide se uma solução incumbente deve ser substituída por uma solução vizinha (para mais detalhes, ver [16]). O algoritmo proposto executa a metaheurística ILS por n_{iter} vezes, conforme mostrado no Algoritmo 1.

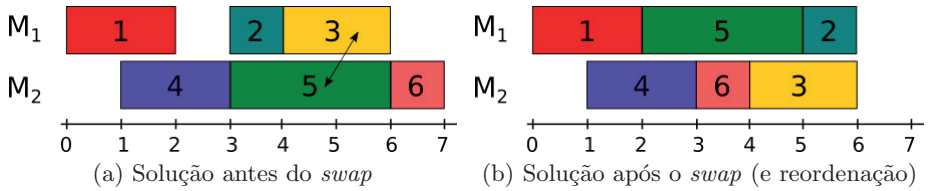
Uma abordagem sequencial é utilizada na geração da solução inicial. Inicialmente, selecionam-se os p locais, depois é realizada a alocação de tarefas aos locais (máquinas) selecionados e, por fim, resolve-se o sequenciamento. Para evitar a repetição da mesma solução incial nas n_{iter} reinicializações do algoritmo, o procedimento de solução inicial implementado escolhe os p locais de maneira aleatória. Para descrever o procedimento de alocação, seja M' o conjunto dos p

Algoritmo 1: BUSCA LOCAL ITERADA COM REINICIALIZAÇÃO

```
1  s_best ← ∅
2  f(s_best) ← ∞
3  para i = 1 to n_iter faça
4      s_i ← s ← ObtemSolucaoInicial()
5      iterILS ← 1
6      enquanto iterILS ≤ n_ils faça
7          s ← BuscaLocal(s)
8          se f(s) < f(s_i) então
9              s_i ← s
10             iterILS ← 0
11         s ← Perturbacao(s_i)
12         iterILS ← iterILS + 1
13     se f(s_i) < f(s_best) então
14         s_best ← s
15 retorna s_best
```

locais selecionados, LJ a lista de tarefas não alocadas e $\bar{s}$ uma solução incompleta (em construção). Para cada local $k \in M'$, identifica-se a tarefa $j' \in LJ$ que puder iniciar seu processamento o mais cedo possível (i.e., considerando o release date e o tempo de término da última tarefa sequenciada em k na solução $\bar{s}$) e insere-se o par (k, j') numa lista CL de alocações candidatas. Então, escolhe-se a alocação $(k^*, j^*) \in CL$ que levar ao menor tempo de término, remove-se a tarefa j^* da lista LJ e esvazia-se CL. O procedimento é repetido até que a lista LJ se torne vazia. Uma vez que todas as tarefas tiverem sido alocadas à uma máquina (ou local), o sequenciamento é resolvido por meio da regra do menor *release date* (ERD).

Após obtida a solução incial, uma busca local baseada em movimentos *swap* entre duas tarefas alocadas a máquinas distintas é realizada. Porém, ao invés de simplesmente realizar a troca de posições, as tarefas são posicionadas na melhor posição do sequenciamento por meio da regra ERD, como ilustrado na Figura 2.



(a) Solução antes do *swap* (b) Solução após o *swap* (e reordenação)

Figura 2: Exemplo de movimento *swap* com reordenamento baseado na regra ERD. Dados da instância: n=6, m=3, p=2, tempos_de_processamento=$[2, 1, 2, 2, 3, 1]$, *release_dates*=$[[0, 3, 4], [3, 3, 5], [4, 4, 5], [2, 1, 4], [2, 2, 4], [6, 3, 3]]$.

Para tornar a busca local eficiente, utilizamos uma estrutura de dados auxiliar que armazena a melhor posição que cada tarefa $j \in J$ pode ser sequenciada em cada máquina $k \in M'$. Além disso, para cada subsequência σ de tarefas consecutivas, armazenamos o tempo total de processamento $P(\sigma)$ e o tempo mais cedo que ela pode iniciar seu processamento $E(\sigma)$. Para uma subsequência σ_j^k contendo uma única tarefa j sequenciada na máquina k, $P(\sigma_j^k)$ e $E(\sigma_j^k)$ são iguais a p_j e r_{jk}, respectivamente. Para subsequências maiores, tais valores são calculados por concatenação de subsequências menores, conforme as equações (9) e (10) abaixo ([20]).

$$P(\sigma' \oplus \sigma'') = P(\sigma') + P(\sigma'') \tag{9}$$

$$E(\sigma' \oplus \sigma'') = \max\{E(\sigma'') - P(\sigma'), E(\sigma')\} \tag{10}$$

Com o uso das estruturas de dados auxiliares mencionadas, os custos das soluções avaliadas durante a busca local podem ser calculados em tempo constante. De modo a exemplificar o uso destas estruturas, seja ρ_{jk} a posição atual da tarefa j no sequenciamento da máquina k, ρ'_{jm} a melhor posição em que a tarefa j pode ser sequenciada na máquina m, e σ_j^k uma subsequência contendo apenas a tarefa j na máquina k. Ao considerar o *swap* entre as tarefas j e l, inicialmente alocadas às máquinas k e m, respectivamente, os tempos de término da máquinas k e m podem ser calculados efetuando-se um conjunto de concatenações. A depender das posições ρ'_{jm} e ρ_{lm} as concatenações necessárias para obter o tempo de término da máquina m podem ser efetuadas de 14 maneiras distintas, conforme ilustrado na Figura 3. O tempo de término da máquina k pode ser calculado de maneira similar.

Por fim, após encontrar o ótimo local, executa-se o procedimento de perturbação. Tal procedimento efetua trocas aleatórias de um local selecionado $k \in M'$ com um local não selecionado $m \in M \setminus M'$, iterativamente. Basicamente, para $i = 1, \ldots, p$, move-se o sequenciamento associado ao i-ésimo local (máquina) para um local de $M \setminus M'$, escolhido aleatoriamente, e atualiza-se o conjunto M'. Após efetuar as trocas de locais, os sequenciamentos de cada máquina (local) é atualizado de acordo com a regra do ERD.

5 Experimentos computacionais

Com o intuito de avaliar os algoritmos e modelos apresentados, experimentos computacionais foram executados em um computador equipado com um processador Intel Core i7-7500U de 2.70 GHz, com 12GB de memória RAM e sistema operacional Windows 10. Os algoritmos foram implementados em C++ e executados usando apenas uma *thread*. Para a resolução do modelo matemático foi utilizado o *solver* Gurobi 7.5.1.

Para avaliar o desempenho dos métodos propostos, foi considerado o conjunto de instâncias criado por [6] que está disponível para *download* em: https://drive.google.com/open?id=0B_-MYN0r5mjqOEdGSEhoLW9Ubk0. Este conjunto é dividido em quatro subconjuntos de modo que os dois primeiros são

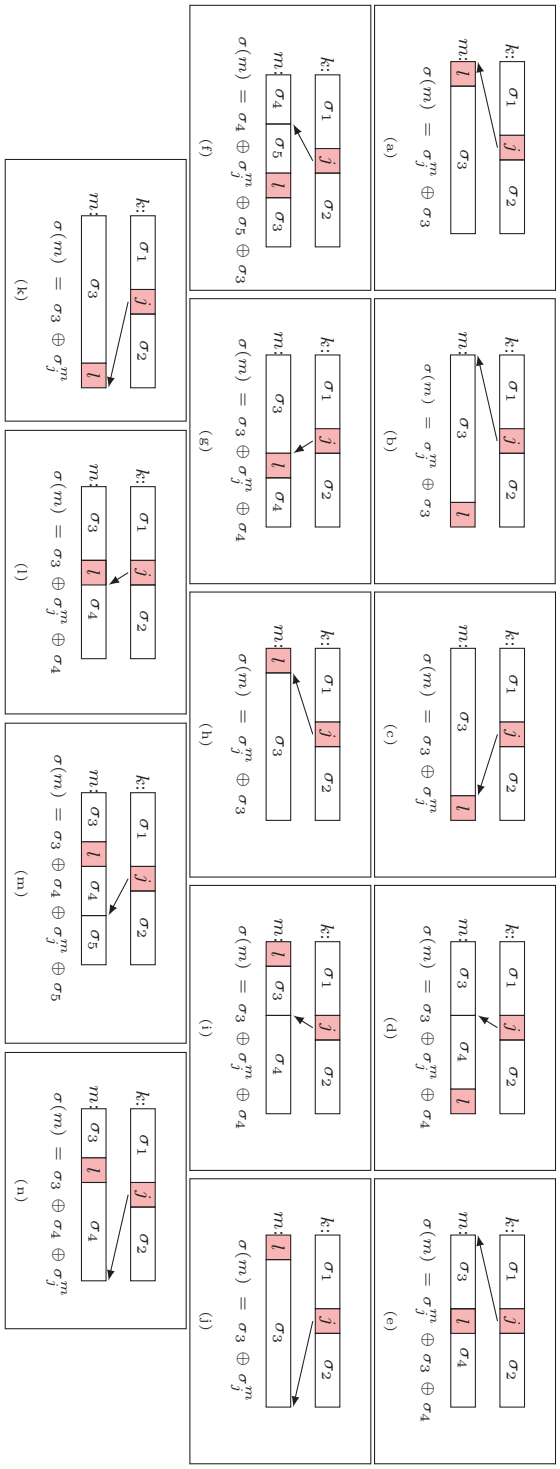


Figura 3: Possíveis concatenações ao mover a tarefa j da máquina k para a máquina m.

compostos por instâncias geradas randomicamente, o terceiro subconjunto é composto por instâncias criadas baseadas em uma rede criada a partir de elementos aleatórios, e o quarto contém instâncias em que as localidades candidatas são escolhidas aleatoriamente dentro de uma área quadrada. Um resumo com as características principais de cada subconjunto de instâncias é mostrado na Tabela 1 a seguir:

Tabela 1: Principais características das instâncias

conjunto	nome	estrutura	#inst.	n	m	p	r_{jk}	p_j
1	small	random, com $\|J\| \neq \|M\|$	50	$[2, 30]$	$[2, 10]$	$[1, 9]$	inteiro	inteiro
2	large	random, com $\|J\| \neq \|M\|$	450	$[4, 299]$	$[5, 60]$	$[2, 50]$	inteiro	inteiro
3	network	network, com $\|J\| = \|M\|^*$	350	$[10, 299]$	$[10, 299]$	$[2, 35]$	inteiro	inteiro
4	planar	planar, com $\|J\| = \|M\|^*$	600	$[10, 300]$	$[10, 300]$	$[2, 35]$	real	inteiro

* O número de locais candidatos é igual ao número de tarefas.

Os tempos de processamento e os *release dates* das tarefas são representados por valores inteiros nas instâncias dos conjuntos 1, 2 e 3, enquanto que para as instâncias do conjunto 4 os valores dos *release dates* são representados por números reais. Em particular, para as instâncias do conjunto 4, os nossos experimentos foram executados considerando valores de *release dates* arredondados para a segunda casa decimal (e multiplicando por 100, para obter valores inteiros).

Para avaliar o desempenho dos métodos propostos, dois experimentos foram realizados. O primeiro tem como o objetivo avaliar o desempenho da formulação TI (1)-(8), enquanto o segundo experimento objetiva a avaliação da metaheurística ILS proposta e descrita na Seção 4.

Com relação aos experimentos com a formulação TI, para cada instância um tempo limite de 300 segundos foi imposto para a execução do *solver*. Além disso, para cada instância o valor inicial de T, que define o horizonte de tempo para o processamento das tarefas, foi obtido através da execução do procedimento de obtenção de uma solução inicial do ILS, detalhado na da Seção 4. Como o procedimento conta com uma componente aleatória, o mesmo foi executado 10 vezes e a melhor solução foi considerada. Com relação ao ILS, o mesmo foi executado 10 vezes e os resultados obtidos são analisados de acordo com as médias e com os melhores resultados dentre as 10 execuções. Para melhor avaliar a qualidade das soluções geradas pelo o ILS, o seguinte procedimento de obtenção de um *lower bound* para instâncias do DPMMSP foi utilizado:

$$LB = \left\lceil \left(\sum\nolimits_{j \in N} p_i / p \right) \right\rceil + \min_{j \in N, k \in M} \{r_{jk}\} \tag{11}$$

Os resultados obtidos tanto para a formulação TI quanto para a metaheurística ILS são apresentados lado-a-lado nas Tabelas 2-5.

Nestas tabelas, cada linha reporta os valores médios/totais para cada grupo de instância, onde a coluna *grupo* indica os números mínimos e máximos de

tarefas das instâncias de cada grupo, a coluna *#inst* apresenta a quantidade de instâncias por grupo, as colunas *#opt* e *#lim* (apenas para as Tabelas 4 e 5) sob a coluna *TI* indicam quantas instâncias foram resolvidas na otimalidade e quantas atingiram o limite de memória sem resolver ao menos a relaxação linear, respectivamente. A coluna *gap (%)* (não se aplica à Tabela 2) mostra o gap médio para as instâncias do grupo que tiveram ao menos a relaxação linear resolvida e a coluna *tempo (s)* mostra o tempo médio de execução, em segundos, ambas sob a coluna *TI*. Para as instâncias em que a execução da formulação TI foi interrompida por limite de memória, foi considerado 300 segundos como tempo de execução (usado no cálculo dos tempos médios). As colunas *#opt* sob as colunas *ILS - resultados médios* e *ILS - melhores resultados* indicam a quantidade média de execuções do ILS que levaram à soluções ótimas e a quantidade total de soluções ótimas provadas para cada grupo de instâncias, respectivamente. As colunas *gap (%)* apresentam os gaps para os melhores *lower bounds* dentre os obtidos pela Equação (11) e pela formulação TI. Por fim, a coluna *tempo (s)* sob a coluna *ILS - resultados médios* indica a média dos tempos médios das 10 execuções do ILS para cada instância.

Tabela 2: Resultados obtidos, TI e ILS - instâncias do tipo *small*

		TI		ILS				
				resultados médios			melhores resultados	
grupo	#inst	#opt	tempo (s)	#opt	gap (%)	tempo (s)	#opt	gap (%)
(1; 5]	10	10	0.11	9.9	0.09	<0.01	10	0.00
(6; 10]	13	13	0.17	9.8	0.17	0.01	13	0.00
(11; 15]	11	11	0.21	8.4	0.94	0.01	11	0.00
(16; 20]	6	6	0.28	8.8	0.89	0.02	6	0.00
(21; 25]	5	5	0.30	10.0	0.00	<0.01	5	0.00
(26; 30]	5	5	0.61	10.0	0.00	<0.01	5	0.00
soma/média	50	50	0.28	9.49	0.35	0.01	50	0.00

Para as instâncias do tipo *small*, a formulação TI foi capaz de resolver todas as 50 na otimalidade e em menos de 0.30 segundo em média, conforme mostrado na Tabela 2. Para esse mesmo conjunto de instâncias, observa-se que o ILS também foi capaz de encontrar soluções ótimas para todas as instâncias, onde a otimalidade foi provada comparando os *upper bounds* encontrados pelo ILS com os *lower bounds* da formulaçao TI e da Equaçao *11*. Em média, o ILS necessitou de 0.01 segundo para cada execução e 9.49 entre 10 execuções levou a soluções ótimas para o problema.

Com relação às instâncias do tipo *large*, é possível observar na Tabela 3 que a formulação TI resolveu na otimalidade 407 das 450 instâncias desse conjunto, incluindo todas com até 75 tarefas. Em média, o tempo necessário para resolução das instâncias foi de aproximadamente 105 segundos. O ILS, por sua vez, encontrou resultados ótimos para 427 das 450 instâncias desse conjunto e o tempo médio de execução do algoritmo foi de apenas 1 segundo. Em particular, todas

Tabela 3: Resultados obtidos, TI e ILS - instâncias do tipo *large*

grupo	#inst	TI			ILS				
					resultados médios			melhores resultados	
		#opt	gap (%)	tempo (s)	#opt	gap (%)	tempo (s)	#opt	gap (%)
(1; 25]	27	27	0.00	0.62	7.7	0.93	0.10	24	0.47
(26; 50]	75	75	0.00	2.68	7.7	0.98	0.41	65	0.52
(51; 75]	78	78	0.00	11.78	8.2	0.61	0.76	71	0.32
(76; 100]	69	67	0.00	35.45	9.2	0.23	0.96	66	0.13
(101; 125]	32	32	0.00	31.66	9.9	0.01	0.52	32	0.00
(126; 150]	41	37	0.00	89.70	9.7	0.08	1.07	41	0.00
(151; 175]	36	27	0.00	138.82	10.0	0.00	0.68	36	0.00
(176; 200]	34	28	0.02	165.11	10.0	0.00	0.66	34	0.00
(201; 225]	12	11	0.10	141.83	10.0	0.00	1.39	12	0.00
(226; 250]	13	9	0.00	186.09	10.0	0.00	1.44	13	0.00
(251; 275]	18	9	0.21	222.19	10.0	0.00	1.85	18	0.00
(276; 300]	15	7	0.13	240.61	10.0	0.00	2.18	15	0.00
soma/média	450	407	0.04	105.55	9.37	0.24	1.00	427	0.12

as 450 instâncias desse conjunto foram resolvidas na otimalidade, seja pela formulação TI ou pela metaheurística ILS. Comparando os resultados obtidos com os resultados obtidos pelas formulações propostas por [6] e [21] e reportados nos seus respectivos trabalhos, observa-se que a TI proposta apresentou um desempenho bem superior ao dessas formulações. A formulação proposta por [6] foi capaz de resolver apenas 26 instâncias do tipo *small*, enquanto que a formulação de [21] resolveu apenas 32 instâncias *small*. Nenhuma das duas formulações foi testada nas instâncias do conjunto *large*.

Tabela 4: Resultados obtidos, TI e ILS - instâncias do tipo *network*

grupo	#inst	TI				ILS				
						resultados médios			melhores resultados	
		#opt	#lim	gap (%)	tempo (s)	#opt	gap (%)	tempo (s)	#opt	gap (%)
(1; 25]	50	50	0	0.00	1.09	9.7	0.09	0.01	50	0.00
(26; 50]	1	1	0	0.00	5.23	10.0	0.00	1.69	1	0.00
(51; 75]	46	46	0	0.00	43.27	6.3	1.37	1.28	31	1.18
(76; 100]	54	50	0	0.08	118.59	9.4	0.17	0.65	53	0.05
(101; 125]	28	18	0	2.93	202.96	6.8	1.03	8.60	20	0.84
(126; 150]	21	7	0	2.27	277.85	9.1	0.24	5.13	20	0.10
(151; 175]	25	14	0	1.43	289.10	9.6	0.07	3.30	24	0.07
(176; 200]	25	16	3	0.45	300.00	9.6	0.05	3.96	25	0.00
(201; 225]	33	23	3	0.29	300.00	10.0	0.00	3.47	33	0.00
(226; 250]	23	14	5	0.28	300.00	10.0	0.00	4.13	23	0.00
(251; 275]	25	3	22	0.00	300.00	10.0	0.00	4.01	25	0.00
(276; 300]	19	0	19	-	300.00	10.0	0.00	6.75	19	0.00
soma/média	350	242	52	0.70	203.17	9.20	0.25	3.58	324	0.19

Diferentemente das instâncias dos tipos *small* e *large*, os conjuntos *network* e *planar* são caracterizadas pelo número de locais candidatos igual ao número de tarefas, o que impacta diretamente no aumento da quantidade de variáveis

na formulação TI. Este impacto pode ser notado nos resultados mostrados nas Tabelas 4 e 5. Por outro lado, o desempenho do ILS se mantém bastante robusto. Em particular, o modelo matemático proposto por [6] foi capaz de resolver apenas duas instâncias do conjunto *network* e duas do conjunto *planar*, enquanto o modelo de [21] não foi capaz de resolver nenhuma instância desses conjuntos.

Com relação às instâncias *network*, apesar da formulação TI ter sido capaz de resolver 242 das 350 instâncias, incluindo todas com até 75 tarefas, é possível observar que nenhuma com mais de 275 teve a relaxação linear resolvida seja por ter atingido o tempo limite ou por ter estourado a memória. O ILS, por sua vez, obteve soluções provadamente ótimas para 324 das 350 instâncias, incluindo todas aquelas com mais de 175 tarefas, e com um tempo médio de execução de menos de 4 segundos. Em particular, o ILS obteve mais dificuldade nas instâncias do grupo $(51; 75]$, mesmo assim, obtendo um gap médio inferior a 2%.

Tabela 5: Resultados obtidos, TI e ILS - instâncias do tipo *planar*

grupo	#inst	TI				ILS				
						resultados médios			melhores resultados	
		#opt	#lim	gap (%)	tempo (s)	#opt	gap (%)	tempo (s)	#opt	gap (%)
(1; 25]	70	9	53	2.97	295.83	9.6	0.37	0.00	68	0.28
(26; 50]	32	0	31	42.99	300.00	9.4	1.49	0.23	30	1.38
(51; 75]	50	0	47	32.87	300.00	5.6	7.25	2.88	28	6.33
(76; 100]	50	0	50	-	300.00	6.7	2.32	6.94	36	1.82
(101; 125]	52	0	52	-	300.00	9.3	0.20	4.54	50	0.09
(126; 150]	52	0	52	-	300.00	9.9	0.03	1.97	52	0.00
(151; 175]	42	0	42	-	300.00	10.0	0.00	1.89	42	0.00
(176; 200]	55	0	55	-	300.00	10.0	0.00	2.60	55	0.00
(201; 225]	53	0	53	-	300.00	10.0	0.00	3.64	53	0.00
(226; 250]	32	0	32	-	300.00	10.0	0.00	6.44	32	0.00
(251; 275]	52	0	52	-	300.00	10.0	0.00	4.23	52	0.00
(276; 300]	60	0	60	-	300.00	10.0	0.00	4.68	60	0.00
soma/média	600	9	579	26.28	299.65	9.21	0.97	3.34	558	0.83

No que se refere às instâncias do conjunto *planar*, apenas 9, todas com $n \leq 25$, foram resolvidas na otimalidade pela formulação TI. Para a maioria das outras instâncias, com $n > 25$, não foi possível resolver nem ao menos relaxação linear do modelo dentro dos limites de tempo e memória. O ILS, mais uma vez, mostrou-se robusto, sendo capaz de provar a otimalidade de 558 das 600 instâncias (incluindo todas com $n > 125$) desse conjunto. O tempo médio requerido por cada execução do ILS foi de cerca de 3.3 segundos.

6 Conclusões e trabalhos futuros

Neste trabalho, foram propostos algoritmos para resolver de forma eficiente um problema integrado de localização de facilidades e de sequenciamento da produção. Em particular, foram propostas uma formulação matemática baseada em variáveis indexas no tempo (TI) e um algoritmo heurístico baseado em busca

local iterada (ILS). Foi mostrado, através de experimentos computacionais, que a formulação TI teve um desempenho satisfatório e que obteve resultados melhores que os obtidos pelas formulações matemáticas da literatura propostas por [6] e [21], sendo capaz de resolver 518 das 1450 instâncias testadas. O algoritmo ILS por sua vez, se mostrou capaz de obter soluções provadamente ótimas para 1359 instâncias e de prover gaps reduzidos para as demais. Devido ao uso de estruturas de dados auxiliares que permitem a avaliação das soluções em tempo constante durante a busca local, o ILS apresentou tempos médios de execução bastante reduzidos, sempre inferiores a 10 segundos, na média. Pesquisa futuras podem ser conduzidas no sentido de propor novos algoritmos exatos (formulações matemáticas, branch-and-cut, branch-and-price) e heurísticos, além do uso integrados das duas abordagens de resolução de problemas, capazes de lidar de forma mais eficiente com as instâncias mais desafiadoras do problema. Outra linha de pesquisa interessante consiste no estudo e adaptação dos métodos propostos para outras variantes do problema estudado.

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Impacto de la productividad y la polifuncionalidad laboral en la gestión de personal: caso aplicado a la industria retail

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Resumen Esta investigación busca evaluar el efecto del fenómeno de aprendizaje y olvido en las decisiones de polifuncionalidad. Este fenómeno se produce cuando empleados polifuncionales pierden productividad en aquellas tareas que realizan con menor frecuencia. En la literatura se recomienda considerar esta disminución de la productividad en las decisiones de polifuncionalidad, con el fin de encontrar alternativas de planificación que mejoren el rendimiento de los empleados. La metodología de solución propone un modelo de programación entera mixta que explícitamente incorpora el fenómeno de aprendizaje y olvido y, también, el uso de personal polifuncional a través del enfoque *k-chaining*. Esta formulación permite determinar cuántos empleados deben ser polifuncionales, en cuántos departamentos adicionales serán entrenados, y qué grado de productividad se espera en cada departamento entrenado. La solución del problema minimiza los costos de subdotación, capacitación y pérdida de productividad. Nosotros presentamos un caso de estudio en la industria retail, en el cual se evaluaron dos experimentos que enfrentaron tres diferentes niveles de variabilidad en la demanda. El primer experimento, generó menores costos debido a que no incorporó la pérdida de productividad asociada al fenómeno de aprendizaje y olvido. El segundo experimento, que sí incorporó dicho fenómeno, generó un mayor costo total pero su solución se ajusta mejor a la operación real de una tienda de retail. Finalmente, dado la incorporación del fenómeno de aprendizaje y olvido, el segundo experimento requirió mayores niveles de polifuncionalidad para minimizar los costos de subdotación y, a su vez, compensar la pérdida de productividad.

Palabras claves: Aprendizaje y olvido, Chaining, Polifuncionalidad, Programación de personal, Retail.

1 Introducción

Los sectores manufactureros y de servicios presentan un rápido crecimiento, son altamente competitivos, y requieren un uso intensivo de los recursos humanos (RRHH). Estos sectores incluyen industrias tales como: automotriz, textil, manufactura, centros de llamadas, salud, retail, entre otras. Henao [1] enuncia que los RRHH son generalmente los recursos productivos más costosos. Por lo tanto, su eficiente gestión permite a las industrias de estos sectores mejorar el nivel de servicio ofrecido a sus clientes y también disminuir los costos laborales. Particularmente, la industria retail debe responder no solo ante fenómenos predecibles como la estacionalidad de la demanda sino también ante fenómenos no predecibles como la incertidumbre de la demanda y el ausentismo no programado de personal. Tales fenómenos producen periodos de sobredotación y subdotación de personal, los cuales tienden a incrementar los costos laborales y deteriorar el nivel de servicio ofrecido a los clientes [2 , 3].

Para la industria retail, varios autores han abordado los problemas de sobredotación y subdotación de personal mediante el uso de personal polifuncional [4 , 5 , 6 , 7]. Note que, el personal polifuncional es aquel que puede trabajar en k departamentos de una tienda (con $k \geq 2$), y la flexibilidad que éstos brindan permite transferir empleados de departamentos sobredotados a aquellos con subdotación de personal. Por lo tanto, su uso eficiente permite minimizar el desajuste entre la demanda y la oferta laboral. Sin embargo, la polifuncionalidad viene con un costo, especialmente en el caso de la polifuncionalidad total, por lo cual, contratar y entrenar empleados en múltiples departamentos puede ser muy costoso.

Además, producto del fenómeno conocido en la literatura como "aprendizaje y olvido", un empleado polifuncional tendrá una pérdida de productividad en aquellos departamentos en los que sea asignado con menor frecuencia. En consecuencia, este proceso de olvido y pérdida de productividad generará un costo para las empresas, ya que ante una menor productividad laboral se requerirá asignar más horas hombre para cubrir un nivel de demanda determinado. Adicionalmente, Azzi y Liang [8] explican que hay rendimientos decrecientes a escala a medida que el número de habilidades aumenta en un empleado. Por lo tanto, niveles de polifuncionalidad muy altos pueden ser imprácticos e innecesarios y, en consecuencia, también se requiere establecer políticas claras que permitan definir cuáles son los niveles de polifuncionalidad más costo-efectivos. Lo descrito hasta aquí, indica que la literatura en retail se ha concentrado principalmente en modelar los beneficios de la polifuncionalidad; sin embargo, es necesario también desarrollar modelos matemáticos que incorporen los costos asociados a la pérdida de productividad ocasionada por el fenómeno de aprendizaje y olvido.

Considerando la necesidad descrita arriba, la contribución que pretende hacer este artículo a la gestión de los recursos humanos en la industria retail, es desarrollar un modelo que determine los niveles de polifuncionalidad que minimicen los costos de entrenamiento y de subdotación de personal; pero también los costos asociados a la pérdida de productividad laboral. Por lo tanto, para un problema de asignación anual de personal, se formuló un modelo de programación entero mixto que explícitamente incorpora el fenómeno de aprendizaje y olvido. Adicionalmente, el modelo asegurará la implementación de la política de flexibilidad laboral conocida como *k-chaining*. Esta

política es ampliamente recomendada en la literatura para enfrentar una demanda incierta [5 , 6]. Bajo la política *k-chaining*, cierto número de empleados serán entrenados en *k* departamentos (con $k \geq 2$), tal que las decisiones de asignación son configuradas a través de un grafo bipartito que involucra deferentes tipos de cadenas cerradas.

Finalmente, esta metodología será aplicada a un caso de estudio en un retail chileno usando un software comercial. El desempeño del enfoque de optimización será evaluado para varios escenarios de variabilidad en la demanda, esto nos permitirá medir los beneficios de la polifuncionalidad ante una demanda incierta, pero también evaluar el impacto del fenómeno de aprendizaje y olvido.

2 Revisión de literatura

La Tabla 1 resume una serie de artículos que han estudiado el efecto de la pérdida de productividad en los problemas de programación de personal que consideran personal polifuncional. A continuación, se explican los elementos presentes en la Tabla 1:

1. *Nivel de decisión de los recursos humanos* (ND-RRHH): Indica el tipo de problema de programación de personal abordado en cada estudio. Puede ser: (i) dotación de personal (D); (ii) planificación de turnos (PT); y (iii) asignación (A). Este último problema se refiere al problema de asignación de personal, el cual es abordado en el presente estudio.
2. *Polifuncionalidad* (PF): Indica si la polifuncionalidad fue modelada cómo un parámetro (Par), o una variable de decisión (Var).
3. *Encadenamiento* (CH): Indica si el estudio evalúa o no los beneficios de la polifuncionalidad a través de la política *k-chaining*.
4. *Fuerza laboral homogénea o heterogénea* (HH): Puede ser: (i) homogénea (Hom), en donde la productividad de un empleado es la misma, independientemente del número de tareas o departamentos en los que sea asignado; y (ii) heterogénea (Het), en el que la productividad de un empleado varía cuando es capacitado para trabajar en múltiples tareas o departamentos.
5. *Modelación de la productividad* (MP): Indica cómo se modela la productividad para considerar el efecto de pérdida/ganancia ocasionado por el uso de personal polifuncional. Según Henao et al. [5] habitualmente se consideran tres tipos de enfoques: (i) aprendizaje y olvido (L/F), en donde la productividad de los empleados se modela como un proceso natural de aprendizaje, olvido y reaprendizaje (ii) matriz de productividad (M), en la cual se asume que cada empleado tiene diferentes niveles de productividad en los departamentos capacitados, lo cual se representa matricialmente; y (iii) productividad constante (E), donde todos los empleados son igualmente productivos en todos los departamentos capacitados.
6. *Costo de pérdida de productividad (CP):* Indica si en el estudio se tuvo en cuenta el costo monetario que representa la pérdida de productividad generada por la polifuncionalidad.
7. *Método* (Met)*:* Indica el método de solución usado en el estudio. Puede ser: (i) heurísticas/metaheurísticas (H); (ii) optimización (OP), (iii) simulación (S), y (iv) Analítico (AN).

8. *Horizonte de planificación (HP):* indica el horizonte de planificación abarcado en el estudio.
9. *Aplicación* (AP): Representa el sector industrial en el cual fue aplicado el estudio. Puede ser: (i) Manufactura (M); (ii) Centros de llamadas (CL); y (iii) Retail (R).

Tabla 1. Estudios que abordan cómo incorporar la pérdida de productividad en las decisiones de polifuncionalidad.

Referencias	**ND-RRHH**	**MF**	**CH**	**HH**	**MP**	**CP**	**Met**	**HP**	**AP**
Attia et al. [9]	D+PT	Par	No	Het	M	Sí	OP+S	4 sem	M
Attia et al. [10]	PT	Par	No	Het	L/F	Sí	H+S	-	M
Bentefouet y Nembhard [11]	A	Par	No	Het	L/F	No	OP	-	M
Kim et al. [12]	A	Par	No	Het	L/F	No	OP	48 hrs	M
Azizi y Liang [8]	A	Par	No	Het	L/F	Sí	H	17 sem	M
Sawhney [13]	PT	Par	No	Hom	E	No	OP	-	M
Bentefouet [14]	PT	Var	No	Het	L/F	No	S	16 sem	M
Nembhard [15]	D +A	Par	No	Het	L/F	No	S	-	M
Attia et al. [16]	D+A	Par	No	Het	M+L/F	Sí	H+S	6 sem	M
Henao et al. [4]	PT	Var	No	Hom	E	No	OP	-	R
Henao et al. [5]	A	Var	Sí	Hom	E	No	OP+H	1 sem	R
Malachowski y Korytkowski [17]	A	Var	No	Het	L/F	No	S	4 sem	M
Mossa et al. [18]	PT	Var	No	Hom	E	No	OP+H	-	M
Munoz y Bastian [19]	PT	Var	No	Het	L/F	Sí	S	-	CL
Valeva et al. [20]	A	Var	No	Het	L/F	No	OP+S	-	M
López y Nembhard [21]	PT	Par	No	Het	M+L/F	No	OP+H	-	M
Korytkowski [22]	D+A	Par	No	Het	L/F	No	H	-	M
Kiassat y Safaei [23]	A	Var	No	Het	L/F	Sí	S	-	M
Biel y Glock [24]	PT	Var	No	Het	L/F	Sí	S	-	M
Henao et al. [6]	A	Var	Sí	Hom	E	No	AN+H	1 sem	R
Porto et al. [7]	D+PT	Var	Sí	Hom	E	No	OP	1 sem	R
Este artículo	***A***	***Var***	***Sí***	***Het***	***L/F***	***Sí***	***OP***	***52 sem***	***R***

La Tabla 1 reporta varios hallazgos en la literatura dignos de destacar. Primero, pocos estudios evaluaron para la industria retail los beneficios de incorporar la polifuncionalidad laboral en la gestión de los recursos humanos [4 , 5 , 6 , 7]. Segundo, muy pocos estudios usaron la política *k-chaining* para estructurar los planes de entrenamiento de los empleados a través de cadenas cerradas [5 , 6 , 7]. Estos estudios fueron aplicados a la industria retail, y reportaron que una política *k-chaining* con *k=2* fue altamente efectiva para minimizar los costos de sobre/subdotación de personal ante escenarios de demanda incierta. Sin embargo, a diferencia del presente trabajo, tales estudios consideraron una fuerza laboral homogénea y, por lo tanto, no se incorporó el efecto de aprendizaje y olvido en los modelos. Además, utilizaron una política *k-chaining* con *k=2*, lo que significa que los empleados solo podían ser capacitados en un máximo de dos departamentos. En cambio, este trabajo usará una política *k-chaining* con $k \geq 2$ y también incorporará en la modelación matemática el proceso de aprendizaje y olvido.

Tercero, la mayoría de los estudios previos fueron aplicados al sector manufactura, y a su vez, la mayoría de éstos modelaron la productividad laboral considerando los efectos del fenómeno de aprendizaje y olvido. Esto demuestra la importancia de estudiar el fenómeno de aprendizaje y olvido, y explorar el impacto que tiene en la industria del sector de servicios, en particular en la industria retail, donde también es observado. Cuarto, la mayoría de los modelos propuestos no consideran la repercusión monetaria que se deriva cuando la productividad de un empleado disminuye a medida que aumenta su nivel de polifuncionalidad. Attia et al. [16] resalta la importancia de incorporar dicho costo en la función objetivo del problema, pues de esta manera se cuantifican mejor los costos y los beneficios asociados al uso de personal polifuncional. En consecuencia, este estudio considerará dicho costo en la función objetivo.

3 Descripción del problema

El problema consiste en diseñar un plan de capacitación idóneo para una fuerza laboral conocida, y a su vez, obtener la asignación semanal de horas de trabajo para un horizonte de planificación de 52 semanas (i.e., un año). De manera novedosa, esta formulación matemática incorporará explícitamente términos en la función objetivo y restricciones que permitan modelar una política de polifuncionalidad *k-chaining* (con $k \geq 2$) y el fenómeno de aprendizaje y olvido. En términos específicos, el reto será resolver la asignación anual de horas-hombre para una tienda de retail, que simultáneamente decide: (i) ¿Cuántos empleados serán polifuncionales?; (ii) ¿En cuántos departamentos adicionales será entrenado cada empleado polifuncional; (iii) ¿Cuántas horas semanales trabajará cada empleado en cada departamento asignado?; y (iv) ¿Cuáles serán los niveles de productividad que tendrá cada empleado en los departamentos donde ha sido entrenado? Es decir, aunque un empleado polifuncional pueda trabajar en dos o más departamentos, no en todos tendrá la misma productividad.

La formulación presentada considera los siguientes supuestos: (i) El costo de subdotación es el mismo para todos los departamentos, y representa el costo por demanda insatisfecha. (ii) Los costos de entrenamiento son los mismos para todos los departamentos. Estos dos primeros supuestos son comunes en retail [5 , 6 , 7 , 25]. (iii) No se considera el ausentismo no programado de personal. (iv) Todos los empleados deben trabajar exactamente 45 horas por semana. (v) Cada empleado está inicialmente capacitado para trabajar en un solo departamento (i.e., personal especialista), pero podría ser entrenado en cualquier departamento de la tienda. (vi) Cada empleado tiene asociado una productividad igual a 1 (i.e., 100%) en el departamento en el que está inicialmente entrenado (i.e., departamento primario). (vii) Se considerarán tres tipos de empleados, los cuales son clasificados de acuerdo su grado de experiencia: Senior, Estándar y Junior. Cada tipo de empleado tendrá un nivel de productividad inicial distinto en los departamentos donde sea entrenado adicionalmente (i.e., departamentos secundarios). Finalmente, la Tabla 2 muestra la notación usada en nuestra formulación del problema.

Tabla 2. Conjuntos, parámetros, y variables del problema abordado.

Conjuntos	
I	Empleados de la tienda, indexado por i
L	Departamentos de la tienda, indexado por l
S	Semanas, indexado por s
I_l	Empleados bajo contrato en el departamento l, $I_l \subset I$
Parámetros generales	
r_{ls}	Número de horas requeridas en la semana s y departamento l, $\forall l \in L, s \in S$
h	Número de horas semanales que un empleado debe trabajar bajo su contrato
m_i	Departamento para el cual el empleado i está inicialmente entrenado, $\forall i \in I$
u	Costo de subdotación por hora
c	Costo de entrenar un empleado para trabajar en cualquier departamento
Parámetros asociados al fenómeno de aprendizaje y olvido	
σ_{il}	Tasa de aprendizaje del empleado i en el departamento l, $\forall i \in I, l \in L$
b_{il}	Factor exponencial para el empleado i del departamento l, $\forall i \in I, l \in L$
n	Número de repeticiones de trabajo
f_{il}	Pendiente de la curva de olvido, empleado i en departamento l, $\forall i \in I, l \in L$
TA	Periodo ininterrumpido de la práctica de la habilidad
TB	Periodo de interrupción después del cual la productividad ha disminuido a su nivel inicial
ξ	Representa el cociente en los periodos TA y TB. Tal que $\xi = TB/TA$
η_{eq}	Número equivalente de repeticiones de trabajo en una fecha específica
U	Costo monetario de desarrollar la productividad de los empleados
λ_{il}	Número de repeticiones de trabajo del empleado i en el departamento l que se debieron realizar si la interrupción no hubiera ocurrido, $\forall i \in I, l \in L$
θ_{il}^{ini}	Productividad inicial del empleado i en el departamento l, al ser asignado por primera vez, $\forall i \in I, l \in L$. Varía de acuerdo si es Senior, Estándar, Junior
Variables	
x_{il}	Igual a 1 si el empleado i es entrenado en el departamento l, $\forall i \in I, l \in L$
v_i	Número de habilidades adicionales del empleado polifuncional i, $\forall i \in I$
ω_{ils}	Número de horas semanales asignadas al empleado i en el departamento l, semana s, $\forall i \in I, l \in L, s \in S$
θ_{il}^{SP}	Productividad del empleado i en el departamento l, al inicio del horizonte de planificación, $\forall i \in I, l \in L$
θ_{il}^{FP}	Productividad del empleado i en el departamento l, al final del horizonte de planificación, $\forall i \in I, l \in L$
k_{ls}	Horas de subdotación en el departamento l y semana s, $\forall l \in L, s \in S$

4 Metodología

La metodología es presentada en dos subsecciones. Con base en el artículo de Attia et al. [16], en la Subsección 4.1 se presenta un conjunto de fórmulas que permiten modelar el fenómeno de aprendizaje y olvido. Luego, usando este conjunto de fórmulas, en la Subsección 4.2 se presenta el modelo de programación entera mixto para resolver el problema antes planteado.

4.1 Modelación del fenómeno de aprendizaje y olvido

Fenómeno de aprendizaje. Según Attia et al. [16], producto del fenómeno de aprendizaje, el tiempo que requiere un empleado para realizar una tarea se reduce cada vez que éste repite dicha tarea. Este fenómeno de aprendizaje representa una evolución de la productividad, la cual puede ser medida en términos de la tasa de aprendizaje σ_{il}, su productividad inicial θ_{il}^{ini} y el tiempo ininterrumpido que realizó la actividad expresado en semanas, n. Esta evolución en la productividad debido al aprendizaje puede ser expresada por la Ecuación (1). Donde el factor exponencial b_{il} se puede calcular mediante la Ecuación (2).

$$\theta_{il}^{SP} = \frac{1}{\left[1+\left(\frac{1}{\theta_{il}^{ini}}-1\right)(n)^{b_{il}}\right]} \tag{1}$$

$$b_{il} = \frac{\log(\sigma_{il})}{\log(2)} \tag{2}$$

Fenómeno de olvido. También se debe considerar la pérdida de productividad generada por la interrupción del trabajo y transferencia de los empleados a otros departamentos. El cambio constante entre departamentos puede ocasionar que se olviden las habilidades asociadas a aquellos departamentos que son asignados con menor frecuencia. Esto se le conoce como el fenómeno de olvido, lo que ocasiona una pérdida de productividad. En este caso la evolución de la productividad se puede expresar a través de la Ecuación (3). Dicha ecuación está en función de la pendiente de la curva del olvido, f_{il}, el número de repeticiones de la habilidad antes de la interrupción expresado en semanas, η_{eq}, y el periodo de interrupción λ_{il}. Donde la pendiente de la curva del olvido f_{il} se calcula usando la Ecuación (4).

$$\theta_{il}^{FP} = \frac{1}{\left[1+\left(\frac{1}{\theta_{il}^{ini}}-1\right)\left(\eta_{eq}\right)^{b_{il}-f_{il}}\left(\eta_{eq}-\lambda_{il}\right)^{f_{il}}\right]} \tag{3}$$

$$f_{il} = -b_{il}\left(b_{il}+1\right)\left[\frac{\log(\eta_{eq})}{\log(\xi+1)}\right] \tag{4}$$

Por lo tanto, debido al fenómeno del aprendizaje y olvido, además del costo de entrenamiento y subdotación; se busca minimizar también el costo de pérdida de productividad al momento de decidir en qué departamentos adicionales deben ser capacitados los empleados.

4.2 Modelo matemático que incorpora *k-chaining* y el fenómeno de aprendizaje y olvido

El modelo de optimización puede ahora ser formulado de la siguiente manera:

$$Min \quad \sum_{i\in I}\sum_{l\in L:l\neq m_i} cx_{il} + \sum_{l\in L}\sum_{s\in S} uk_{ls} + \sum_{l\in L:l\neq m_i} U\left[\frac{\sum_{i\in I}\left(\theta_{il}^{FP}-\theta_{il}^{SP}\right)}{\sum_{i\in I}\theta_{il}^{SP}}\right]x_{il} \tag{5}$$

s.a.

$$\sum_{i\in I}\theta_{il}^{FP}\omega_{ils} + k_{ls} \geq r_{ls} \qquad \forall l\in L, \forall s\in S \tag{6}$$

$$\sum_{l\in L}\omega_{ils} = h \qquad \forall i\in I, \forall s\in S \tag{7}$$

$$\omega_{ils} \leq hx_{il} \qquad \forall i\in I, \forall l\in L, \forall s\in S \tag{8}$$

$$x_{il} = 1 \qquad \forall i\in I, \forall l\in L: l=m_i \tag{9}$$

$$v_i = \sum_{i\in L:l\neq m_i} x_{il} \qquad \forall i\in I \tag{10}$$

$$\sum_{i\in l_l} v_i = \sum_{i\in\left\{I-I_l\right\}} x_{il} \qquad \forall l\in L \tag{11}$$

$$\theta_{il}^{SP} = \frac{1}{\left[1+\left(\frac{1}{\theta_{il}^{ini}}-1\right)\left(n\right)^{b_{il}}\right]} \qquad \forall i\in I, \forall l\in L \tag{12}$$

$$\theta_{il}^{FP} = \frac{1}{\left[1+\left(\frac{1}{\theta_{il}^{ini}}-1\right)\left(\eta_{eq}\right)^{b_{il}-f_{il}}\left(\eta_{eq}-\lambda_{il}\right)^{f_{il}}\right]} \quad \forall i\in I, \forall l\in L \tag{13}$$

$$0 \le \theta_{il}^{SP} \le 1 \qquad \forall i \in I, \forall l \in L \tag{14}$$

$$0 \le \theta_{il}^{FP} \le 1 \qquad \forall i \in I, \forall l \in L \tag{15}$$

$$x_{il} \in \{0,1\} \qquad \forall i \in I, \forall l \in L \tag{16}$$

$$v_i \ge 0 \qquad \forall i \in I, \forall l \in L \tag{17}$$

$$\omega_{ils} \ge 0 \qquad \forall i \in I, \forall l \in L \tag{18}$$

$$k_{ls} \ge 0 \qquad \forall i \in I, \forall l \in L \tag{19}$$

La función objetivo (5) minimiza los siguientes costos: (i) entrenamiento; (ii) subdotación del personal; y (iii) pérdida de productividad. Las restricciones (6) y (19) producen el nivel de subdotación de personal (no negativo) asociado con cada departamento. Las restricciones (7) aseguran que cada empleado trabaje exactamente la cantidad de horas requeridas por su contrato en cada semana. Las restricciones (8) imponen que cada empleado sea asignado a trabajar solo en los departamentos para los cuales fue entrenado. Las restricciones (9) determinan el departamento en el cual está capacitado inicialmente cada empleado. Las restricciones (10) indican, para cada empleado, en cuántos departamentos adicionales fue entrenado; podría continuar como especialista o convertirse en polifuncional. Las restricciones (11) garantizan que para cada departamento *l,* el número de empleados polifuncionales que pertenecen a él, será igual a la cantidad de empleados pertenecientes a otros departamentos pero que fueron entrenados para también trabajar en el departamento *l*. Las restricciones (10) y (11) garantizan la formación de cadenas cerradas a través de un enfoque *k-chaining*. Las restricciones (12) representan la evolución de la productividad bajo el fenómeno del aprendizaje, mientras las restricciones (13) representan la evolución de la productividad bajo el fenómeno del olvido. Finalmente, las restricciones (14) - (19) definen el dominio de cada variable del problema.

5 Caso de estudio, resultados y discusión

Esta sección se subdivide en tres partes. Primero, se indican los datos usados para resolver nuestro caso de estudio. Segundo, se presentan los experimentos y métricas desempeño que permitirán evaluar el impacto de la evolución de la productividad en las decisiones de polifuncionalidad. Tercero, se presentan los resultados de la implementación de la metodología y también un análisis de resultados.

5.1 Caso de estudio

Este caso de estudio considera datos reales, procesados y simulados asociados a una tienda de retail chilena.

Datos reales. Se consideran 6 departamentos y 30 empleados contratados, i.e., $|L| = 6$ y $|I| = 30$. Tal que en cada departamento hay un número inicial de empleados especialistas I_l. Además, todos los empleados deben trabajar 45 horas a la semana, i.e., *h=45,* y el horizonte de planificación es de 52 semanas, $|S| = 52$. Respecto a los costos laborales, el costo mínimo de entrenamiento es igual a *c=US$1 semana/empleado* [5], el costo de subdotación es igual a *u=US$15/h*, y el costo asociado a la pérdida de productividad es igual a *P=US$2 semana/empleado*.

Datos procesados. Estos datos son requeridos para modelar el fenómeno de aprendizaje y olvido. Este caso de estudio considera tres tipos de empleados según su productividad inicial, estos son: Sénior, Junior y Estándar. Estos tendrán una productividad inicial (θ_{il}^{ini}) igual a 0.8, 0.7 y 0.6 respectivamente, en los departamentos adicionales en los que sean entrenados. A su vez, todos los empleados tendrán una productividad inicial, $\theta_{il}^{ini} = 1$, en el departamento en el cual ya están entrenados. Adicionalmente, en este estudio se consideró que la tasa de aprendizaje es constante para cada empleado y departamento, y su valor es $\sigma_{il} = 0.8$. De igual manera, se asumió que el número de repeticiones de trabajo antes del inicio del estudio (*n*) es igual a 1 debido a que los empleados aún no se encuentran entrenados en habilidades adicionales [16]. El factor exponencial b_{il} y la pendiente de la curva del olvido f_{il} no presentan diferencias entre departamentos. Finalmente, para modelar la evolución de la productividad teniendo en cuenta el efecto del aprendizaje y olvido, se consideraron $\xi = 3$ y $n_{eq} = 2$. Todos los valores indicados son típicamente reportados en la literatura.

Datos simulados. Mediante datos históricos se conoce que la demanda en horas (r_{ls}) por departamento *l* y semana *s* sigue una distribución normal. Con el propósito de evaluar el impacto de la variabilidad de la demanda en los resultados de esta metodología, se consideraron tres escenarios de variabilidad; representados mediante los siguientes coeficientes de variación (CV): 10%, 20% y 30%. Luego, para cada CV y siguiendo una distribución de probabilidad normal truncada en cero (para evitar valores negativos), se realizó una simulación de Monte Carlo para obtener los valores de demanda para cada una de las 52 semanas del horizonte de planificación.

5.2 Experimentos y métricas de desempeño

Experimentos. Con el fin de comparar el impacto de la evolución de la productividad en las decisiones de polifuncionalidad, se definieron los siguientes dos experimentos:

1. *Experimento 1*: Los empleados pueden ser entrenados en uno o más departamentos adicionales, pero se modelarán como una fuerza laboral homogénea. Es decir,

todos los empleados tienen una productividad laboral igual 1 en todos los departamentos donde sean entrenados.

2. *Experimento 2*: Los empleados pueden ser entrenados en uno o más departamentos adicionales, pero se modelarán como una fuerza laboral heterogénea. Tal que se incorpora el efecto del fenómeno de aprendizaje y olvido.

Cabe resaltar dos cosas. Primero, el Experimento 2 es equivalente a la metodología propuesta en este artículo. Segundo, para cada experimento, se consideran los tres escenarios de variabilidad en la demanda definidos previamente (CV = 10%, 20% y 30%).

Métricas de desempeño. Con el fin de evaluar el desempeño de las soluciones, se utilizarán dos métricas, las cuales permitirán medir los requerimientos de polifuncionalidad.

1. *Porcentaje de empleados polifuncionales*: calcula el número de empleados polifuncionales requeridos, en relación con el total de empleados en la tienda.

$$\%ME = \frac{N°Empleados\_polifuncionales}{|I|}.100 \tag{20}$$

2. *Porcentaje de polifuncionalidad total*: se calcula como el número de habilidades adicionales entrenadas, en relación con el número máximo de habilidades posibles de entrenar.

$$\%TM = \frac{\sum_{i\in I}\sum_{l\in L: l\neq mi} x_{il}}{|I|\left(|L|-1\right)}.100 \tag{21}$$

5.3 Resultados y discusión

La formulación propuesta fue escrita en AMPL y resuelta usando el software ILOG CPLEX 12.9.0. A su vez, se empleó un PC con un procesador Intel (R) Core (TM) i5-7200U CPU @ 2.50 GHz 2.71 GHz. y 4GB de RAM. Para todos los escenarios se llegó a optimalidad en menos de 60 segundos. Además, la Tabla 3 muestra el número de variables y restricciones que se generó en cada uno de los escenarios probados. Note que, como la estructura del problema no cambia de un escenario a otro, el tamaño del modelo es el mismo en todos ellos.

Tabla 3. Características del modelo.

Experimento	%CV	Variables Binarias	Variables Continuas	Restricciones
1	10	150	10 341	10 035
	20	150	10 341	10 035
	30	150	10 341	10 035
2	10	150	10 342	10 036
	20	150	10 342	10 036
	30	150	10 342	10 036

El fenómeno de aprendizaje y olvido tiene un impacto en las decisiones de polifuncionalidad. Por lo cual, a partir de un análisis de costos y las métricas de desempeño %ME

y %TM, se evaluaron y compararon los resultados obtenidos en los Experimentos 1 y 2. Primero, para el Experimento 2, se reportó que la productividad final (θ_{il}^{FP}) obtenida para los tres tipos de empleados (en los departamentos secundarios) fue la siguiente: Senior, 0.9; Estándar, 0.8; y Junior, 0.7. Esto indica que, aquellos modelos que asumen una fuerza laboral homogénea como la descrita en el Experimento 1, pueden entregar soluciones que no se ajustan a la realidad de las empresas.

Continuando con el análisis, la Tabla 4 presenta los resultados obtenidos para cada experimento; de allí se desprenden los siguientes análisis. Primero, y para ambos experimentos, se observa que a medida que aumenta el coeficiente de variación (%CV) aumentan los requerimientos de polifuncionalidad (i.e., %ME y %TM). Este resultado es intuitivo, pues a mayores niveles de incertidumbre en la demanda, una mayor inversión en flexibilidad laboral (i.e., polifuncionalidad) permitirá minimizar el desajuste entre la oferta y la demanda de personal. Segundo, para el Experimento 2, se observa que los niveles de polifuncionalidad requeridos son más altos que en el Experimento 1. Este resultado es interesante, pues indica que la incorporación del fenómeno de aprendizaje y olvido exige mayores niveles de flexibilidad para compensar el hecho que los niveles de productividad finales de los empleados polifuncionales (en los departamentos secundarios) ya no son el máximo, i.e., son menores a 1.

Tercero, se debe destacar que aun cuando dos escenarios tengan el mismo valor de %ME, los %TM no tienen por qué ser iguales. Por ejemplo, para %CV=20, se observa que en ambos experimentos se obtuvo %ME=50; sin embargo, el %TM es mayor en el Experimento 2. Esto significa que en ambos experimentos se requirió el mismo número de empleados polifuncionales, pero en el Experimento 2 los empleados polifuncionales se entrenaron en mayor número de departamentos adicionales. De forma general, los resultados reflejados en Tabla 4 muestran que en el Experimento 2 el número máximo de habilidades adicionales entrenadas en un empleado polifuncional fue ν=4, mientras que para el Experimento 1 este número fue ν=3.

Tabla 4. Resultados obtenidos y medidas de desempeño asociados a los Experimentos 1 y 2.

Exp.	%CV	N° Empleados polifuncionales					%ME	%TM	Costo anual (US$)			
		ν=1	ν=2	ν=3	ν=4	Total			ET	ST	PP	Total
1	10	8	1	-	-	9	30	7	10	57 360	-	57 370
	20	13	2	-	-	15	50	13	19	140 760	-	140 779
	30	14	5	1	-	20	67	18	27	163 320	-	163 347
2	10	5	3	2	1	11	37	14	21	62 124	5	62 150
	20	4	7	4	-	15	50	20	30	151 854	8	151 892
	30	5	6	4	2	17	57	25	37	176 256	10	176 303

De la Tabla 4 también se desprende un cuarto análisis asociado a los costos incurridos en cada experimento y CV. Se observa que en el Experimento 2 hay una mayor inversión en polifuncionalidad y, por lo tanto, los costos de entrenamiento (ET) son mayores. Además, en ambos experimentos, se observa que los costos de subdotación (ST) aumentan a medida que aumenta el CV. Sin embargo, el Experimento 1 registra costos de subdotación inferiores al Experimento 2. Este resultado se produce porque el Experimento 1 asume que los empleados polifuncionales son homogéneos y tienen un nivel de productividad máximo en cada uno de los departamentos entrenados (i.e.,

$\theta_{il}^{SP} = \theta_{il}^{FP} = 1$). Es decir, bajo el Experimento 1 la oferta de horas-hombre está 100% disponible, lo cual no ocurre en el Experimento 2 donde el fenómeno de olvido genera una pérdida de productividad. En consecuencia, el Experimento 2 entrega niveles de polifuncionalidad más ajustados a la realidad y, a su vez, no subestima los costos de subdotación. Finalmente, producto de los mayores costos de entrenamiento (ET), de subdotación (ST), y a la incorporación del costo virtual asociado a la pérdida de productividad (PP) generada por el fenómeno de aprendizaje y olvido, el Experimento 2 siempre reporta un costo total mayor respecto al Experimento 1.

6 Conclusiones

En el presente estudio se propuso un modelo de programación entera mixta para resolver un problema de asignación anual de personal que explícitamente incorpora el fenómeno de aprendizaje y olvido y, también, el uso de personal polifuncional a través del enfoque *k-chaining*. El objetivo fue medir y evaluar el impacto del fenómeno de aprendizaje y olvido en las decisiones de polifuncionalidad. El caso de estudio fue una tienda de retail chilena, para un periodo de planificación de un año, en el cual se evaluaron dos experimentos que enfrentaron tres diferentes niveles de variabilidad en la demanda. El primer experimento no incorporó el fenómeno de aprendizaje y olvido y, a su vez, asumió una fuerza laboral homogénea con productividad máxima. El segundo experimento sí incorporó el fenómeno de aprendizaje y olvido y, por lo tanto, modeló una fuerza laboral heterogénea.

Este caso de estudio arrojó varios resultados de interés. Primero, el Experimento 1 siempre reportó costos menores en comparación al Experimento 2. Esto sucede porque el Experimento 1 subestima los costos de entrenamiento y de subdotación de personal, al asumir (de manera poco probable) que todos los empleados polifuncionales siempre tienen máxima productividad en todos los departamentos adicionales donde fueron entrenados. Por otra parte, el Experimento 2 requirió mayores niveles de polifuncionalidad para compensar la pérdida de productividad ocasionada por el fenómeno del olvido. A su vez, dado que los empleados polifuncionales reportaron productividades finales menores a 1 en los departamentos adicionales donde fueron entrenados, los niveles de subdotación reportados fueron mayores con relación al Experimento 1. Estos resultados son interesantes, pues demuestran la importancia de incorporar el fenómeno de aprendizaje y olvido en las decisiones de polifuncionalidad, lo cual lidera la consecución de soluciones más ajustadas a la realidad.

Adicionalmente, se evidenció que, a mayor variabilidad en la demanda, mayores niveles de polifuncionalidad son requeridos. Sumado a esto, para el Experimento 2, el número de habilidades adicionales entrenadas en un empleado polifuncional tomó un máximo de cuatro, mientras que para el Experimento 1 este máximo fue igual a tres.

Finalmente, para futuras investigaciones, sería interesante agregar los siguientes análisis: (1) incorporar en simultáneo decisiones de contratación de personal, lo cual permitiría ajustarse mejor a escenarios de alta variabilidad en la demanda; (2) considerar explícitamente en la formulación matemática condiciones de demanda estocástica, lo

cual permitiría obtener soluciones robustas y factibles ante cambios en dicho parámetro; y (3) realizar un análisis de sensibilidad sobre los parámetros de costos utilizados, lo cual permitiría explorar cambios en la estructura de solución del problema.

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Two-stage stochastic optimization model for personnel days-off scheduling using closed-chained multiskilling structures

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Abstract. This paper addresses a days-off scheduling problem that incorporates multiskilling decisions using a 2-chaining policy. The generated closed-chained multiskilling structures minimize the expected training and over/understaffing costs, while assigning rest days between working days to single-skilled and multiskilled employees. This research provides a suitable methodology for a wide range of industries where the main problem is to meet the demand requirements the seven days of the week, but where the employees cannot work daily. The methodology is structured in two steps. First, we develop a deterministic mixed integer linear programming model. Second, the deterministic model is reformulated as a two-stage stochastic optimization model in order to explicitly incorporate demand uncertainty. Our methodology was applied in a case study associated to a Chilean retail store. We use real data but also simulated data to represent various demand variability scenarios. Results showed that the model was able to do the days-off scheduling decisions cost-effectively for a planning horizon of two weeks. Additionally, it was found that the levels of understaffing and overstaffing can vary between weekdays (Monday to Friday) and weekend. Finally, we also observed that the 2-chaining policy was cost-effective in all scenarios; however, when there are very high levels of demand variability, it can be interesting to explore k-chaining with $k \geq 2$ and/or to hire more employees.

Keywords: Multiskilling, Chaining, Days-off scheduling, Workforce flexibility, Retail services.

1 Introduction

The service sector currently contributes more than 60% of production and employment in the world and has a share in international trade of approximately 20% [1], so their systems should be optimized and highly studied. One of the processes with the greatest impact on a service organization is the personnel scheduling. However, in this sector is complex to establish effective personnel scheduling systems that ensure an adequate

customer service level (CSL) and make a most efficient use of resources due to the high level of uncertain demand and unscheduled staff absenteeism. These phenomena produce periods of over- and under-staffing (i.e., staffing levels that are higher or lower than required, respectively) that can directly lead to an increase labor costs and, in turn, deteriorate the customer service levels [2 , 3 , 4].

A source of labor flexibility, supported by the literature, that seeks to counteract the effects of staff shortage/surplus in a service company is to incorporate multiskilled employees who can work on multiple task types (or store departments) [2 , 5],. In addition, chaining is a cost-effective policy that allows to transfer available multiskilled employees from overstaffed departments to understaffed departments. In this policy, a certain number of employees are trained to work in two or more departments, such that these allocation decisions are configured through a bipartite graph that involves different chains types. Particularly, the 2-chaining policy is based on the fact that certain employees are trained to work in a maximum of two departments. This policy has been shown to be one of the most cost-effective and recommended in the literature, because it does not lead to the over-training of the employees and optimizes the multiskilling approach [6].

Also, as mentioned above, the uncertainty in the staff demand is a relevant phenomenon in the context of the personnel scheduling problem in the service companies. Thus, to make decisions under uncertain demand, is useful to apply a two-stage stochastic optimization (TSSO) model that explicitly considers such uncertainty.

Given the above, the intended contribution of this paper to the personnel scheduling problem in the service sector is a model that determines the multiskilling levels that minimize the expected costs associated with training and over/understaffing. The proposed methodology is structured in two steps. First, a days-off scheduling problem is initially formulated as a deterministic mixed integer linear programming model (MILPM), which assigns rest days between working days to single-skilled and multiskilled employees over a two-week planning horizon. Note that, since 2-chaining policies have shown to be very effective in terms of providing flexibility to address uncertain demands, the training plan for employees will be structured through closed chains. Second, the MILPM is reformulated as a TSSO model in order to explicitly incorporate demand uncertainty. Then, our methodology is applied to a case study of a Chilean retail store using commercial software. The performance of the optimization approach is assessed for various demand variability scenarios in order to measure the benefits of the closed-chain multiskilling structures to face uncertainty.

2 Literature Review

There is a wide range of authors who proposed different mathematical models to solve the personnel scheduling problems. Table 1 characterizes a series of articles published in recent decades to obtain an accurate contextualization of the state of the art. The studies are described by the following characteristics:

i) *Personnel scheduling problem* (PSP): based on the classification made by Henao et. al [7], we indicate the type of problem addressed in each study. May be: (a) staffing

(S); (b) shift scheduling (SS); (c) days-off scheduling (DOS); (d) tour scheduling (TS); or (e) assignment (A).

ii) *Multiskilling* (MS): this criterion indicates whether the multiskilling was modeled through a parameter (Par), i.e. as model input, or a decision variable (Var).

iii) *Chaining* (CH): according to the classification presented in Henao et al. [7], the chain types used in each study are indicated. These could be: (a) closed long chain (CLC), one multiskilled employee per task type forming one chain that connects all task types; (b) closed short chain (CSC), a subset of multiskilled employees that connects just a subset of task types; (c) open chain (OC), a long chain which it was not closed; and (d) all-for-one (AxO), where all multiskilled employees are trained for assignment to a single task type.

iv) *Workforce type* (WFT): May be: (a) homogeneous workforce (HO), which means that the productivity of an employee does not change if he or she is assigned different task types; and (b) heterogeneous workforce (HT), which means that, if employees increase the number of task types they are able to work, then productivity can decrease.

v) *Uncertainty* (U): Indicates whether or not the problem posed by study considers: (a) demand uncertainty (D); and/or (b) supply variability (O) (i.e., unscheduled staff absenteeism).

vi) *Methods* (ME): Indicates the solution method used. May be: (a) simulation (S); (b) heuristics (H); (c) traditional optimization (OPT); (d) analytic (AN); and (e) metaheuristics (M).

vii) *Uncertainty modeling approach* (UMA): Indicates the modeling approach that was used to explicitly incorporates uncertainty into an optimization model. May be: (a) two-stage stochastic optimization (TSSO); (b) robust optimization (RO); and (c) closed-form equation (CF).

viii) *Application (AP):* We have found different fields in which the authors do their research, such as hospitals (H), retail (R), airports (AI), cyber security (CS), services (S), and manufacturing (MA).

Table 1 shows that multiskilling is a source of labor flexibility very used to address the personnel scheduling problems. Complementing it with chaining undoubtedly has a high impact to minimize the levels of over/understaffing. However, even though the chaining represents a growing trend according to the state of the art, there is still a need for more work to prove its effectiveness. On the other hand, the authors focus on shift scheduling or tour scheduling, so days-off scheduling represents a gap in the literature. This represents a field of interest, since days-off scheduling is a need in a wide range of industries where the main problem is to meet the demand requirements the seven days of the week, but where the employees cannot work daily. Examples include restaurants, power plants, hospitals, and retail stores. In addition, few studies explicitly incorporated the demand uncertainty into the mathematical formulation.

The contribution of this work is twofold. First, we evaluate the impact of closed-chained multiskilling structures on days-off scheduling in the service sector, particularly for the retail industry. Second, we propose a TSSO approach to make the uncertain demand explicit. It is important to note that our modeling will consider multiskilling as

a decision variable, thus, the model will decide how many employees will be multi-skilled and in which store departments, while at the same time will produce a set of closed chains. This will allow to consider a much wider range of assignment possibilities and providing a much more efficient way to satisfy the staff demand.

Table 1. Characteristics of published studies related to personnel programming problem.

Reference	PSP	MS	CH	WFT	U	ME	UMA	AP
Brusco and Johns [8]	S+SS	Par	CLC,CSC	HT	-	OPT	-	S
Alvarez-Valdes et al. [9]	TS	-	-	HO	-	OPT+H	-	AI
Inman et al. [5]	S+A	Par	CLC,CSC, OC, AxO	HO	O	S	-	MA
Jordan et al. [10]	A	Par	CLC	HT	D	S	-	MA
Kabak et al. [11]	S+TS	-	-	-	.-	OPT+S	-	R
Campbell [12]	DOS	Par	-	HT	D	OPT+H	TSSO	-
Paul and McDonald [13]	S+A	Var	CLC, CSC	HT	D	OPT+M	CF	H
McDonald [14]	A	Par	OC	HT	-	OPT	-	MA
Henao et al. [15]	A	Var	CLC,CSC	HO	D	OPT+H	RO	R
Ying and Tsai [16]	A	Par	-	HO	-	OPT+H	-	MA
Restrepo et al. [17]	TS	Par	-	HO	D	OPT+M	TSSO	-
Altner et al. [18]	S+SS	-	-	-	D	OPT+H	TSSO	CS
He et al. [19]	S+SS	-	-	HO	D	OPT	TSSO	H
Felberbauer et al. [20]	S+A	Par	-	HT	D	OPT+M	TSSO	MA
Altner et al. [21]	DOS	Var	-	HO	D	OPT+M	TSSO	CS
Henao et al. [7]	A	Var	CLC, CSC	HO	D	AN+H	CF	R
Porto et al. [2]	S+TS	Var	CLC,CSC	HO	D	OPT	-	R
This paper	***DOS***	***Var***	***CLC, CSC***	***HO***	***D***	***OPT***	***TSSO***	***R***

3 Problem description

The problem we propose to study consists in generating a training plan for a retail store, and then, obtaining a schedule of resting and working days for each them over a two-week planning horizon. It is assumed that each department has hired a set of employees initially single-skilled and therefore trained to work in a single department. In more specific terms, our problem will be to solve a biweekly DOS that simultaneously decides how many single-skilled employees should be multiskilled, in which second department to form closed-chained multiskilling structures, and how to assign working and resting days to each employee. In addition, each employee can work maximum five consecutive days and must work a given number of weekly hours as specified by his/her contract. The objective is to minimize the expected costs associated with training and over/understaffing. Table 2 shows the notation used in the formulation of the problem.

Table 2. Sets, parameters, and variables of the days-of scheduling problem.

Sets	
I	Store employees, indexed by i
L	Store departments, indexed by l
I_l	Employees under contract in department l, indexed by i, $\forall\, l \in L$
S	Set of weeks, indexed by s
D	Days of the biweekly planning horizon, indexed by d, $\{M1, Tu1, W1, Th1, F1, S1, Su1, M2, Tu2, W2, Th2, F2, S2, Su2\}$
D_s	Set of days of the week s
$D5_d$	Set of consecutive days after the day d
D^+	Set of maximum consecutive days, indexed by d, $\{M1, Tu1, W1, Th1, F1, S1, Su1, M2, Tu2\}$
Parameters	
r_{ld}	Number of daily hours demanded in department l on day d, $\forall l \in L, d \in D$
h	Number of weekly hours an employee must work according to his/her contract
t	Number of working hours an employee must work per day
m_i	Department for which employee i was initially trained, $\forall i \in I$
μ	Staff shortage cost per hour (equivalent to the expected cost of lost sales)
o	Staff surplus cost per hour (equivalent to the opportunity cost of idle employee-hours)
c	Training cost of an employee to work in any department
Variables	
x_{il}	Equal to 1 if employee *i* is trained for department *l*, otherwise 0, $\forall i \in I, l \in L$
v_i	Equal to 1 if employee *i* is multiskilled, otherwise 0, $\forall i \in I$
ω_{ild}	Number of working hours assigned to employee i in department l in day $d, \forall i \in I, l \in L, d \in D$
y_{id}	Equal to 1 if employee i works in day d, otherwise 0, $\forall i \in I, d \in D$
k_{ld}	Staff shortage in hours in department l on day d, $\forall l \in L, d \in D$
δ_{ld}	Staff surplus in hours in department l in day $d, \forall l \in L, d \in D$
z_i	Equal to 1 if employee *i* has days off in the first weekend (S1, Su1), and equal to 0 if employee has days off in the second weekend (S2, Su2), $\forall i \in I$

Our formulation incorporates the following assumptions: (1) Employees can be trained in a maximum of two store departments. (2) Employees have the same level of productivity for each department (i.e., homogeneous workforce). (3) Employees may work a maximum of five consecutive days. (4) The planning horizon has 14-days (two weeks). (5) All employees must work exactly five days per week with 9-hour work shifts per working day. (6) Unscheduled staff absenteeism is not considered. (7) The daily hours demand in each department is a random parameter. (8) All employees are initially trained in single department. (9) The cost of staff shortage is the same for all departments, which is a common assumption on the field. (10) The cost of staff surplus is an

opportunity cost for idle staff, and it is also equal for all departments. (11) Training costs are equal for each department.

4 Methodology

In this section we present a deterministic version of our mixed integer linear programming model for solving the days-off scheduling problem with chaining as just described above. Later, we will introduce the necessary modifications to transform the model into a two-stage stochastic formulation incorporating demand uncertainty for solving the same problem.

4.1 Deterministic model

The deterministic model can now be formulated as follows:

$$Min \quad \sum_{i\in I}\sum_{l\in L: l\neq m_i} cx_{il} + \sum_{d\in D}\sum_{l\in L}(\mu k_{ld} + o\delta_{ld}) \tag{1}$$

s.t.

$$\sum_{i\in I}\omega_{ild} + k_{ld} - \delta_{ld} = r_{ld} \qquad \forall l \in L, d \in D \tag{2}$$
$$\omega_{ild} \leq t x_{il} \qquad \forall i \in I, l \in L, d \in D \tag{3}$$
$$\sum_{l\in L}\omega_{ild} = t y_{id} \qquad \forall i \in I, d \in D \tag{4}$$
$$\sum_{d\in D_S} y_{id} = 5 \qquad \forall i \in I, s \in S \tag{5}$$
$$y_{id} + \sum_{\overline{d}\in D5_d} y_{i\overline{d}} \leq 5 \qquad \forall i \in I, d \in D^{+} \tag{6}$$
$$y_{id} \leq 1 - z_i \qquad \forall i \in I, d \in D\{S1, Su1\} \tag{7}$$
$$y_{id} \leq z_i \qquad \forall i \in I, d \in D\{S2, Su2\} \tag{8}$$
$$x_{il} = 1 \qquad \forall i \in I, l \in L: l = m_i \tag{9}$$
$$v_i = \sum_{l\in L: l\neq m_i} x_{il} \qquad \forall i \in I \tag{10}$$
$$v_i \leq 1 \qquad \forall i \in I \tag{11}$$
$$\sum_{i\in I_l} v_i = \sum_{i\in\{I-I_l\}} x_{il} \qquad \forall l \in L \tag{12}$$
$$y_{id} \in \{0,1\} \qquad \forall i \in I, d \in D \tag{13}$$
$$x_{il} \in \{0,1\} \qquad \forall i \in I, l \in L \tag{14}$$
$$z_i \in \{0,1\} \qquad \forall i \in I \tag{15}$$
$$\omega_{ild} \geq 0 \qquad \forall i \in I, l \in L, d \in D \tag{16}$$
$$k_{ld} \geq 0 \qquad \forall l \in L, d \in D \tag{17}$$
$$\delta_{ld} \geq 0 \qquad \forall l \in L, d \in D \tag{18}$$
$$v_i \geq 0 \qquad \forall i \in I \tag{19}$$

In this formulation the objective function (1) minimizes the following three biweekly costs: personnel training, staff shortage, and staff surplus. Constraints (2) along with the constraints (17) and (18) yield the levels of staff shortage/surplus associated with each department. Constraints (3) ensure that individual employees be assigned to work in, and only in, departments they have been trained for. Constraints (4) ensure that employees work exactly the number of hours required in each working day. Constraints from (5) to (8) implement days off scheduling constraints developed by Altner et al. [21]. Constraints (5) indicate that each employee must work five days per week. Note

that, constraints (4) and (5) ensure that employees work exactly the weekly number of hours required by the employment contract, i.e., h. Constraints (6) indicate that each employee can work a maximum of 5 consecutive days. Constraints (7) and (8) ensure that each employee has at least one weekend off. Constraints (9) determine the department each employee was originally trained for. Constraints (10) determine whether an employee is multiskilled or single-skilled. Constraints (11) ensure that an employee is trained in a maximum of two departments. Constraints (12) indicate that the number of employees who have been trained in the department *l* (from other departments) should be equal to the number of multiskilled employees belonging to the department *l*. Constraints (11) and (12) ensure that employees are assigned to closed-chained multiskilling structures. Finally, constraints (13)-(19) define the domain of each problem variable.

4.2 Two-stage stochastic optimization model

The two-stage stochastic optimization model (TSSO) arises when full knowledge about the distribution of uncertain demand is available and is defined with two variable types: first stage and second-stage. The first-stage variables are related to decisions that are made before the realization of the uncertain parameters become available, that is, decisions such as the training of employees in a second department. The second-stage variables are related to decisions that are made after the realization of daily demand is known, that is, decisions such as personnel assignment to minimize the levels of over/under-staffing. The second-stage variables depend on the first-stage variables and the uncertain parameter.

To solve this problem the sample average approximation (SAA) approach will be implemented. This approach creates one set of second-stage variables for every possible scenario of demand. The quality of the SAA is related to how large is the set of samples. The set of scenarios comes from the continuous distribution of the random parameters ξ represented by $\xi \in \Xi$, where Ξ is the set of scenarios generated, which forms the SAA problem. Below, we present the TSSO version of the deterministic formulation (1)-(19), written as follows:

$$Min \quad \sum_{i\in I}\sum_{l\in L:l\neq m_i} cx_{il} + \frac{1}{|\Xi|}\left[\sum_{\xi\in\Xi}\sum_{d\in D}\sum_{l\in L}\mu k_{ld}(\xi) + o\delta_{ld}(\xi)\right] \tag{20}$$

s.t.

$$\sum_{i\in I}\omega_{ild}(\xi) + k_{ld}(\xi) - \delta_{ld}(\xi) = r_{ld}(\xi) \qquad \forall l \in L, d \in D, \xi \in \Xi \tag{21}$$

$$\omega_{ild}(\xi) \leq tx_{il} \qquad \forall i \in I, l \in L, d \in D, \xi \in \Xi \tag{22}$$

$$\sum_{l\in L}\omega_{ild}(\xi) = ty_{id} \qquad \forall i \in I, d \in D, \xi \in \Xi \tag{23}$$

$$\sum_{d\in D_S} y_{id} = 5 \qquad \forall i \in I, s \in S \tag{24}$$

$$y_{id} + \sum_{\overline{d}\in D5_d} y_{i\overline{d}} \leq 5 \qquad \forall i \in I, d \in D^+ \tag{25}$$

$$y_{id} \leq 1 - z_i \qquad \forall i \in I, d \in D\{S1, Su1\} \tag{26}$$

$$y_{id} \leq z_i \qquad \forall i \in I, d \in D\{S2, Su2\} \tag{27}$$

$$x_{il} = 1 \qquad \forall i \in I, l \in L: l = m_i \tag{28}$$

$$v_i = \sum_{l\in L:l\neq m_i} x_{il} \qquad \forall i \in I \tag{29}$$

$$v_i \leq 1 \qquad \forall i \in I \tag{30}$$

$$\sum_{i\in I_l} v_i = \sum_{i\in\{I-I_l\}} x_{il} \quad \forall l \in L \tag{31}$$
$$y_{id} \in \{0,1\} \quad \forall i \in I, d \in D \tag{32}$$
$$x_{il} \in \{0,1\} \quad \forall i \in I, l \in L \tag{33}$$
$$z_i \in \{0,1\} \quad \forall i \in I \tag{34}$$
$$\omega_{ild}(\xi) \geq 0 \quad \forall i \in I, l \in L, d \in D, \xi \in \Xi \tag{35}$$
$$k_{ld}(\xi) \geq 0 \quad \forall l \in L, d \in D, \xi \in \Xi \tag{36}$$
$$\delta_{ld}(\xi) \geq 0 \quad \forall l \in L, d \in D, \xi \in \Xi \tag{37}$$
$$v_i \geq 0 \quad \forall i \in I \tag{38}$$

The objective function (20) aims to minimize the training cost (first-stage decisions) and the expected biweekly cost of staff shortages and surpluses (second-stage decisions). In this TSSO model the decision about which employees will be multiskilled is done in the first stage and this will affect the levels of staff shortage/surplus in the second stage. The main objective in the TSSO is to choose the first-stage variables in order to minimize the sum of first stage costs and the expected value of the random second stage costs. Constraints (21)-(38) are accordingly extended from (2)-(19) to consider the uncertainty demand and scenario-dependent second stage variables.

5 Case study, results, and discussion

This section presents the case study used to validate our methodology, as well as its computational implementation.

5.1 Case study

The case study is based on real and simulated data, which is derived from a retail store in Chile. This retail store currently has employees hired in specific departments. Each department currently constitutes a store business unit and at that level is where the store's training and employee scheduling decisions are made.

The real data corresponds to the information related to the store size, the number of departments, the number of employees hired in each department, employment-contract characteristics, mean values on the daily demand in each department, as well as costs related to the model. Regarding the simulated data, these include information about the random parameter of daily hours demand in each store department, which corresponds to the uncertain parameter in our model. The following is a detailed description of the data.

Real data. The case study considers a retail store with 6 departments and 30 employees, that is, $|L| = 6$ and $|I| = 30$. The employment contract stipulates that an employee must comply with 45 hours per week ($h = 45$) and 9 hours per working day ($t = 9$). Regarding the cost parameters, there is a minimal training cost value per employee ($c = US\$1\ biweek/employee$), which has been estimated according to Henao et al. [7 , 15 , 22]. This minimal training cost allows interpreting the results as an upper bound on the potential contribution of multiskilling to store performance [2 , 23]. Finally, the

costs related to under/over-staffing are estimated on an hourly basis and are $u = US\$60/h$ and $s = US\$15/h$, respectively.

Simulated data. Since the TSSO model (20)-(38) is solved by a SAA method, this implies that we use a Monte Carlo simulation to randomly generate 60 scenarios for the parameters of daily hours demand in each department $r_{l_d}(\xi), \forall l \in L, \forall d \in D, \xi \in \Xi$ such that $\Xi = 60$. We consider that the probability density function (pdf) for the demand of each department follows a normal distribution and it is zero-truncated to prevent generating negative demand values. Finally, in the simulation Monte Carlo, we consider three representative variability levels for demand in a department: coefficient of variation $CV = 10\%, 30\%, 50\%$.

5.2 Results and discussion

This section presents the results of the TSSO model presented in Section 4.2 according to the conditions presented in the case study described in Section 5.1. The model was coded in AMPL and solved using the commercial software CPLEX 12.9.0 running through NEOS-server for 8 h (restrictive). Considering the running conditions, we obtained optimality gaps of less than 0.3%.

The results and discussion of our methodology are divided into the following three subsections: models' size and computational times; multiskilling results; and days-off scheduling results. The last two subsections only present results associated with the TSSO model.

Model's size and computational times. As it was mentioned before, the run time of the TSSO model was restricted to 8 hours. Thus, for each coefficient of variation of the staff demand (*CV* = 10%, 30% and 50%) the same computational time was maintained. Regarding the deterministic model, the running time was of approximately 14.3 seconds for each CV. Table 3 presents the differences in model size between the deterministic model (DT) and the associated TSSO model.

Table 3. Comparison between the deterministic and stochastic models.

Element	TSSO	DT
Constraints	156 738	3 102
Binary variables	600	600
Continuous variables	161 322	2 730

Multiskilling results. The purpose of this subsection is to evaluate the multiskilling requirements associated with each CV. Thus, for each CV, these requirements were measured through three metrics and are presented in Table 4. First, we present the number of multiskilled employees required in each store department. Second, we calculate the percentage of multiskilled employees (*%ME*), which represents the number of multiskilled employees required, in relation to the total number of hired employees. Third,

the percentage of total multiskilling (*%TM*) is calculated, representing the number of additional skills trained, in relation to the theoretical maximum number feasible (at the store level).

Table 4. Multiskilling results and metrics with different demand uncertainty levels.

	Store department							
	1	2	3	4	5	6		
%CV	**No. multiskilled employees**						***%ME***	***%TM***
10	3	2	2	2	2	3	47	9
30	5	5	2	3	3	5	77	15
50	7	5	3	3	4	8	100	20

We observed that the number of multiskilled employees per store department, %ME, and %TM increase as the %CV of demand increases. This result is intuitive because the greater the variability in demand, there will be greater opportunities to transfer multiskilled employees from overstaffed departments to understaffed departments.

In detail, when demand variability is the lowest (i.e., CV=10%), the %ME is almost equal to 50%. In turn, when demand variability is equal to 30%, the %ME is equal to 77%. Finally, when demand variability is the highest (i.e., CV=50%), the optimal number of multiskilled employees per department is equal to its total staff, i.e., ME=100%. This result is interesting since it indicates that when there are very high levels of demand variability, a 2-chaining policy cannot be sufficient to minimize the costs of over/understaffing. That is, it can be interesting to evaluate two new strategies: (1) to explore *k*-chaining policies where certain employees can be trained to work in two or more departments [24]; and (2) to hire more employees.

Days-off scheduling results. For the second week of our planning horizon and each CV in the demand, Figure 1 shows a comparison between the number of employees assigned and the over/understaffing hours in each store department. A plot of the first week, not shown in the figure, would indicate the same general tendency. Figure 1 shows that those days where there is more staff demand (i.e., weekend), a greater number of employees are assigned.

In detail, when $CV = 10\%$, we observed that from Monday to Friday, less employees are assigned in comparison to the weekend; this is reasonable given that on Saturday and Sunday there are higher personnel requirements. But as *CV* increases, the number of employees assigned to weekdays (Monday to Friday) versus weekends become similar. This result is not surprising, since at higher levels of variability in demand, the model decides to assign almost the same amount of staff every day, which is a conservative decision. In addition, this makes sense since the over/understaffing costs do not vary according to the day of the week.

Regarding of the demand satisfaction, Figure 1 shows that as CV increases, the levels of over/understaffing are also greater. This is also a predictable behavior, since, if there is greater demand uncertainty, it is more difficult to adjust the staff supply to the staff demand. Finally, the high levels of staff shortage during the weekend suggest that it is

convenient to hire more employees and/or to allow multiskilled employees to be trained in more than one additional department.

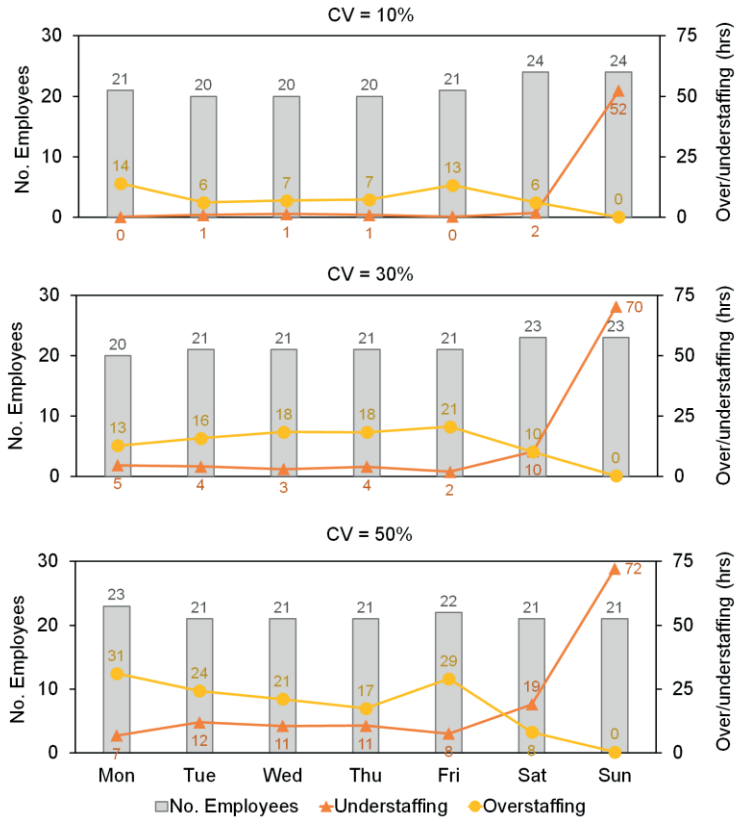

Fig. 1. Comparison between the number of employees assigned and the over/understaffing hours in each department for different levels of uncertainty in the demand.

6 Conclusions

This research presents a new methodology to determine the multiskilling levels that minimize the expected costs associated with training and over/understaffing. In a novel way we ensure the training plans using the approach 2-chaining. The problem consists in assigs to rest days between working days to single-skilled and multiskilled employees over a two-week planning horizon. The proposed methodology initially formulates a deterministic mixed integer linear programming model, and secondly, presents a stochastic version of the model (TSSO). The TSSO model is validated through a case study associated to a Chilean retail store. The performance of the TSSO model is assessed for various demand variability scenarios in order to measure the benefits of the closed-chain multiskilling structures to face uncertainty.

Regarding the results associated with the model's size and its computational times, it was found that the stochastic version of the model led to an increase in the computational times. However, the TSSO times are acceptable since personnel training decisions are tactical-strategic and, thus, made in medium and long-term planning horizons.

Regarding the results associated with the multiskilling requirements, we observe an intuitive result, since the required number of multiskilled employees grows with the demand coefficient of variation. In addition, we found that when there are very high levels of demand variability, it can be interesting to explore *k*-chaining policies where certain employees can be trained to work in two or more departments.

Regarding the results associated with the days-off scheduling problem, we observe (as expected) that those days with the highest demand also have a greater number of assigned employees. Thus, there is a greater staff supply on weekends. In addition, we can also observe that when there are very high levels of demand variability, increases in multiskilling are not enough, since increases in capacity are also required to minimize the levels of staff shortage. That is, it is necessary to hire more employees.

As regards future research, we think it would be valuable to include into the model staffing decisions, where the amount of personnel to be hired is decided. Also, it can be interesting to evaluate *k*-chaining policies where certain employees are trained to work in *k* departments with $k \geq 2$. Finally, the TSSO model could also explicitly incorporate the uncertainty in the staff supply, that is, unscheduled staff absenteeism.

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Beneficios de la polifuncionalidad laboral en la industria retail: Enfoque "k-chaining" con incertidumbre en la demanda

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Resumen En la industria retail, la estacionalidad de la demanda, su incertidumbre, y el ausentismo no programado de personal producen un desajuste entre la oferta y la demanda, que puede aumentar considerablemente los costos de sobredotación y subdotación de personal. El uso de personal polifuncional es una fuente de flexibilidad atractiva para minimizar tal descalce. Este trabajo presenta un modelo de programación lineal entera mixta para estructurar las habilidades polifuncionales de un conjunto de empleados. Para incorporar explícitamente la incertidumbre de la demanda desarrollamos un enfoque de optimización estocástica en dos etapas. Posteriormente, mediante simulación Montecarlo se analiza el desempeño de las soluciones para distintos niveles de variabilidad en la demanda. Para probar el rendimiento del enfoque estocástico propuesto, este se compara con las soluciones de dos enfoques miopes: polifuncionalidad cero y polifuncionalidad total. La metodología propuesta es aplicada a un caso de estudio en una tienda de retail chilena, usando datos reales y simulados. Nuestros resultados mostraron que el enfoque propuesto reportó el máximo beneficio posible para todos los niveles de variabilidad. Finalmente, brindamos información a los responsables de la toma de decisiones para abordar dos aspectos claves de la polifuncionalidad: cuánto agregar y cómo se debe agregar.

Palabras claves: Polifuncionalidad, Chaining, Programación de personal, Programación estocástica, Retail.

1 Introducción

El sector servicios, y en particular la industria de retail, deben responder no solo ante fenómenos predecibles como la estacionalidad de la demanda sino también ante fenómenos impredecibles como su incertidumbre y el ausentismo no programado de personal. Ambos fenómenos complican la planificación eficiente de los recursos humanos (RRHH), pues dificultan el ajuste entre la oferta y la demanda de personal. Por lo que incluso empresas con un sistema efectivo de programación de turnos de trabajo pueden enfrentar problemas de sobredotación y subdotación de personal en varios momentos durante el curso de una semana [1, 2, 3, 4]. La literatura en esta área sugiere que varios autores han abordado efectivamente los problemas de sobredotación y subdotación usando personal polifuncional.

En una tienda retail, el personal polifuncional es uno que tiene la habilidad para trabajar en *k* departamentos (con $k \geq 2$), lo cual permite al gerente operacional transferir empleados polifuncionales de departamentos con sobredotación de personal a aquellos con presencia de subdotación. Muchos investigadores han encontrado que el *k-chaining* es la política más costo-efectiva para estructurar una fuerza laboral polifuncional [2, 3, 5, 6, 7, 8]. Específicamente el *k-chaining* implica que ciertos empleados estén capacitados para trabajar en *k* departamentos con $k \geq 2$ y que estas decisiones de asignación de empleados y departamentos se configuran a través de un grafo bipartito que involucra cadenas largas cerradas (CLC) y/o cadenas cortas cerradas (CCC). En una CLC hay un empleado polifuncional por departamento formando una única cadena que conecta todos los departamentos de la tienda, mientras que en una CCC hay un subconjunto de empleados polifuncionales que conecta un subconjunto de departamentos. Particularmente, la política *2-chaining* ha sido reportada como la política más popular y recomendada en la literatura [2, 3, 7, 8, 9]. Bajo esta política todos los empleados polifuncionales están entrenados en máximo dos departamentos, es decir, $k=2$ (ver Figura 1).

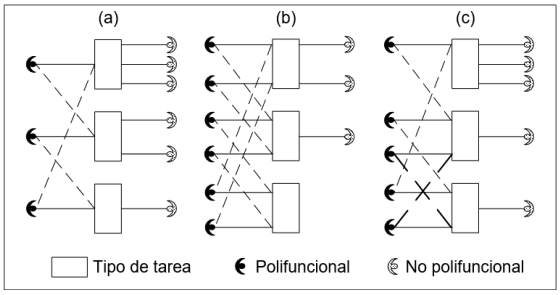

Figura 1. Configuraciones *2-chaining*: (a) Una CLC; (b) Dos CLC idénticas; y (c) Una CLC y Una CCC. Fuente: Henao et al. [2].

Pocos estudios han explorado los beneficios de la implementación de *políticas k-chaining* con $k \geq 2$. La Figura 2 muestra ejemplos de configuraciones de este tipo. En Wang y Zhang [10] los autores evaluaron y compararon el rendimiento de CLCs usando una política *2-chaining* versus una política *k-chaining* con $k>2$. Ellos encontraron que, a mayores niveles de variación en la demanda, las políticas *k-chaining* con $k>2$ conservaron altos niveles de rendimiento a diferencia de las políticas *2-chainnig*. Esto sugiere que ante altos niveles de incertidumbre en la demanda es más beneficioso tener un mayor grado de flexibilidad en el encadenamiento. A su vez, sus resultados también mostraron que hay rendimientos decrecientes a escala a medida que *k* aumenta, es decir, los rendimientos cuando $k=5$ y $k=6$ son casi idénticos. Por lo tanto, niveles de polifuncionalidad muy altos pueden ser imprácticos e innecesarios, y, en consecuencia, también se requiere establecer políticas claras que permitan definir los niveles de polifuncionalidad más costo-efectivos.

En este trabajo se propone una metodología novedosa para evaluar los beneficios del encadenamiento con incertidumbre en la demanda. Primero, el problema se formula como un Modelo de Programación Lineal Entera Mixta (MPLEM) determinístico. Nuestra formulación se diferencia de estudios previos en la literatura puesto que se definen estructuras de polifuncionalidad a través de políticas *k-chaining* con $k \geq 2$ garantizando la formación de cadenas cerradas (CLC y/o CCC). Segundo el MPLEM se

reformula en un modelo de optimización estocástica de dos etapas (TSSO, por sus siglas en ingles) para incorporar la incertidumbre de la demanda. Finalmente, se aplica la metodología propuesta para un caso de estudio en una tienda de retail chilena, considerando distintos niveles de variabilidad en la demanda.

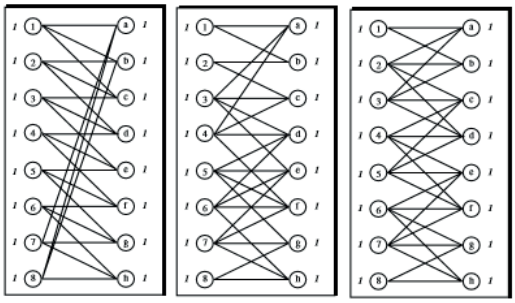

Figura 2. Configuraciones *k-chaining* con $k \geq 2$. Fuente: Iravani et al. [6].

2 Revisión de literatura

La Tabla 1 presenta una revisión de estudios consultados que han tratado el problema de polifuncionalidad en la planificación de los RRHH. A continuación, se definen los elementos presentes en la Tabla 1:

1. *Nivel de decisión de los RRHH* (ND): Indica el tipo de problema de programación de personal abordado en cada estudio. Puede ser: (a) dotación de personal (D); (b) asignación de turnos diarios (AT); (c) asignación de días de descanso (ADD), (c) programación semanal de turnos (PST), donde los días de descanso y turnos de trabajo son asignados simultáneamente; y (d) asignación (A). Este último problema se refiere al problema de asignación de personal, el cual es abordado en nuestro estudio.
2. *Polifuncionalidad* (PF): Indica si la polifuncionalidad fue modelada cómo un parámetro (Par), o una variable de decisión (Var).
3. *Incertidumbre en la demanda* (ID): Indica sí el problema consideró variabilidad en la demanda.
4. *Incertidumbre en la oferta* (IO): Indica sí el problema consideró variabilidad en la oferta (es decir, ausentismo no programado de personal).
5. *Encadenamiento* (*Chaining*)*:* Indica si el estudio usó una política estricta de *2-chaining* o si usó una política *k-chaining* con $k \geq 2$. También se indica si el estudio no consideró ninguna de las dos políticas.
6. *Número de habilidades* (H): Indica si en el estudio existe una restricción para limitar el número máximo de habilidades en los empleados polifuncionales. El estudio puede ser: (a) *restringido* (R), cada empleado polifuncional puede tener solo dos habilidades y (b) *no restringido* (NR), la cantidad de habilidades no está restringida, es decir, cada empleado polifuncional puede tener más de dos habilidades en total.

7. *Método* (M)*:* Indica el método de solución usado. Pueden ser: (a) heurísticas (H); (b) simulación (S); (c) optimización (OPT); y (d) analítica (AN); y (e) Procesos de Markov (MP).
8. *Modelación de la incertidumbre* (MI): Indica el enfoque que se utilizó para evaluar la incertidumbre asociada a los parámetros de un modelo. (1) *In-optimización*: enfoques que incorporan la incertidumbre explícitamente en la formulación matemática, pueden ser: (a) ecuación cerrada (EC); (b) programación estocástica (PE); (c) optimización robusta (OR); y (d) optimización distributiva robusta (ODR). (2) *Post-optimización*: enfoques que evalúan el impacto de la incertidumbre una vez se tiene la solución determinística del problema, pueden ser: (a) análisis de sensibilidad (AS); y (b) evaluación de múltiples escenarios (EME).
9. *Aplicación* (AP): Indica el sector o industria de aplicación del estudio. Pueden ser: (a) Envío de carga (CA); (b) Manufactura (MA); (c) Central eléctrica (CE); (d) Centros de llamadas (CL); (e) Tecnología (TE); (f) Salud (SA); y (g) Retail (RE).

Tabla 1. Características de estudios publicados con polifuncionalidad en la gestión de los RRHH.

Referencia	ND	PF	ID	IO	*Chaining*	H	M	MI	AP
Cai y Li [11]	D+PST	Par	No	No	No	R	H	-	CA
Agnihothri et al. [12]	A	Par	No	No	No	R	S	-	MA
Eitzen y Panton [13]	PST	Par	No	No	No	NR	A	-	CE
Bokhorst et al. [14]	A	Var	No	No	2-chaining	R	OPT+S	-	MA
Hopp et al. [9]	A	Var	Si	No	2-chaining	R	S+MP	AS	MA
Wallace y Whitt [5]	D	Var	No	No	k-chaining	NR	S+A	-	CL
Iravani et al. [6]	A	Par	Si	No	k-chaining	NR	S	AS	CL
Yang [15]	A	Par	No	Si	k-chaining	NR	S	AS	MA
Sayin y Karabati [16]	A	Par	Si	Si	No	NR	OPT+S	AS	-
Heimerl y Kolisch [17]	D+PST	Par	No	No	No	NR	OPT+H	-	TE
Campbell [18]	A+ADD	Par	Si	No	No	NR	OPT+H	AS	SA
Simchi-Levi y Wei [7]	A	Par	Si	-	2-chaining	R	A	EC	MA
Parvin et al. [19]	A	Par	No	No	k-chaining	NR	H	-	MA
Deng y Shen [20]	A	Par	Si	-	k-chaining	NR	OPT+S+A	EME	MA
Paul y McDonald [21]	D+A	Var	Si	No	2-chaining	R	OPT+H+A	EME	SA
Gnanlet y Gilland [22]	D+A	Var	Si	No	2-chaining	R	OPT	PE, EC	SA
Wang y Zhang [10]	A	Par	Si	-	k-chaining	NR	OPT+A	ODR, AS	MA
Henao et al. [1]	PST	Var	No	No	No	NR	OPT	-	RE
Cuevas et al. [23]	PST	Par	No	No	No	NR	OPT	-	RE
Henao et al. [2]	A	Var	Si	No	2-chaining	R	OPT+H+S	OR	RE
Liu [24]	D+A	Par	Si	No	2-chaining	R	OPT+S	PE	MA
Agrali et al. [25]	A	Par	No	No	No	NR	OPT+A	-	SA
Taskiran y Zhang [26]	D+PST	Var	No	No	No	NR	OPT	-	CL
Mac-Vicar et al. ([27]	PST+A	Par	No	Si	No	NR	OPT+H	AS	RE
Henao et al. [3]	A	Var	Si	No	2-chaining	R	OPT+H+S	EC	RE
Porto et al. [8]	D+PST	Var	Si	No	2-chaining	R	OPT	AS	RE
Este artículo	***A***	***Var***	***Si***	***No***	***k-chaining***	***NR***	***OPT***	***PE***	***RE***

2.1. Principales vacíos encontrados

En la extensa literatura sobre polifuncionalidad laboral es posible identificar los siguientes vacíos.

Primero, la Tabla 1 muestra que a pesar de que existen múltiples artículos que estudian la polifuncionalidad, la mayoría de ellos incorporan la polifuncionalidad como un dato de entrada y no como una variable que indique si un empleado será entrenado en un determinado conjunto de habilidades o no. Esto tiene el efecto negativo de restringir las consideraciones de diseño y limitar las posibilidades de encontrar mejores soluciones. Del mismo modo, también se muestra que hay estudios que evalúan los beneficios de la polifuncionalidad mediante el enfoque *chaining* ($k=2$ o $k\geq2$). Sin embargo, solo algunos de estos estudios incorporan la polifuncionalidad como una variable de decisión con el propósito de desarrollar políticas de *k-chaining* [2, 3, 5, 8, 9, 10, 14, 21, 22].

Segundo, la Tabla 1 también muestra que hay varios estudios que evalúan los beneficios de la polifuncionalidad ante incertidumbre, ya sea en la demanda o en la oferta. Sin embargo, solo [2, 3, 7, 10, 22, 24] incorporaron explícitamente esta incertidumbre dentro de la formulación matemática (es decir, enfoque *in*-optimización). Por lo tanto, las soluciones obtenidas en tales trabajos se consideran buenas y robustas ante distintos niveles de incertidumbre. No pasa esto con los estudios que evaluaron la incertidumbre usando un enfoque *post*-optimización, pues tales trabajos no pueden garantizar robustez o factibilidad de la solución determinística encontrada ante presencia de incertidumbre.

Tercero, se observa en la Tabla 1 que la mayoría de los estudios que consideran el enfoque *chaining* restringen el número de habilidades de los empleados polifuncionales a un máximo de dos. Además, a excepción de Wallace y Whitt [5] e Iravani et al. [6] cuyos estudios se aplican en *call centers*, los estudios que implementan *k-chaining* con $k\geq2$ se focalizan principalmente en el sector manufactura. Se debe destacar que, a diferencia del sector manufactura donde el problema de asignación de recursos se formula típicamente como un sistema balanceado (igual número de nodos de oferta y de demanda), en la industria retail el problema de asignación es de naturaleza desbalanceado (mayor número de nodos de oferta (empleados) que nodos de demanda (departamentos)). Por lo cual, el enfoque *k-chaining* en retail exige nuevos desafíos metodológicos.

En resumen, la exhaustiva revisión de literatura muestra que para la industria retail no hay estudios que en simultáneo evalúen los potenciales beneficios de usar políticas *k-chaining* con $k\geq2$, que modelen la polifuncionalidad como una variable de decisión, y que también incorporen explícitamente dentro la formulación matemática la incertidumbre de la demanda. Este trabajo abordará en simultáneo todos los vacíos listados.

3 Descripción del problema

El problema que se propone estudiar en este trabajo consiste en planificar una fuerza laboral polifuncional a nivel estratégico para la industria retail. Para un horizonte de planificación semanal, el problema consiste en diseñar un plan de capacitación idóneo para una fuerza laboral conocida y que inicialmente está capacitada para trabajar en un solo departamento (es decir, personal especialista), a través de estructuras *k-chaining* donde los empleados polifuncionales puedan ser entrenados en dos o más departamentos y donde cada empleado debe trabajar un número determinado de horas semanales según lo especificado en su contrato. La solución a este modelo debe proporcionar una

solución eficiente al problema de asignación que nos indicará cuantas horas semanales debe trabajar cada empleado en los departamentos donde recibió capacitación. La solución del problema decidirá cuántos empleados deben ser especialistas y cuántos polifuncionales, cuántas habilidades adicionales debe adquirir cada empleado polifuncional, y bajo qué niveles de incertidumbre de la demanda es más beneficioso una política 2-chaining o k-chaining con k≥2.

Nuestra formulación considera los siguientes supuestos: (1) La demanda semanal por departamento tiene una distribución de probabilidad conocida y se asume correlación cero entre las demandas por departamento. (2) La demanda del personal para cada departamento puede ser parcialmente satisfecha. Esto implica que el costo de subdotación de personal se incluye en la función de costo total. (3) se incorpora también los costos de sobredotación de personal y capacitación en la función de costo total. (4) Se supone que los costos de subdotación, sobredotación y capacitación son los mismos para todos los departamentos. (5) No hay ausentismo de personal. (6) Todos los empleados tienen el mismo contrato y, por lo tanto, trabajan la misma cantidad de horas semanales. (7) El problema determinístico de asignación de personal es totalmente equilibrado, es decir, que las horas disponibles para la asignación en cualquier departamento son iguales al valor en horas de la demanda media de ese departamento. (8) Inicialmente todos los empleados son especialistas (9) Los empleados polifuncionales pueden trabajar en dos o más departamentos. (10) Los empleados son homogéneos, lo que significa que la productividad individual de cada uno es la misma.

4 Metodología

4.1 Modelo de optimización determinista usando enfoque *k-chaining* con k≥2

En esta subsección presentamos el MPLEM para resolver el problema de asignación de personal con encadenamiento como se describió anteriormente. A continuación, se presenta la notación matemática del problema.

Conjuntos

I Empleados de la tienda, indexado por i

L Departamentos de la tienda, indexado por l

S Escenarios de demanda, indexado por s

I_l Empleados bajo contrato en el departamento l, indexado por i, $\forall l \in L$

Parámetros

$r_l(s)$ Demanda aleatoria semanal en horas para el departamento l y escenario s, $\forall l \in L, s \in S$

$\overline{r_l}$ Valor medio de la demanda de horas semanales en el departamento l, $\forall l \in L$

c Costo de capacitación de un empleado para trabajar en cualquier departamento

u Costo de escasez de personal por hora en cualquier departamento

b Costo de excedente de personal por hora en cualquier departamento

h Número de horas semanales que el empleado debe trabajar según contrato laboral

m_i Departamento para el cual el empleado *i* fue inicialmente capacitado, $\forall i \in I$

Variables

x_{il} Igual a 1 si el empleado *i* es capacitado para trabajar en el departamento *l*, 0 de lo contrario, $\forall i \in I, l \in L$

v_i Número de habilidades adicionales del empleado *i*, $\forall i \in I$

ω_{il} Horas semanales de trabajo asignadas al empleado *i* en el departamento *l*, $\forall i \in I, l \in L$

κ_l Escasez de personal en horas semanales en el departamento *l*, $\forall l \in L$

δ_l Excedente de personal en horas semanales en el departamento *l*, $\forall l \in L$

El MPLEM determinista se puede formular de la siguiente manera:

$$Min \quad \underbrace{\sum_{i \in I} \sum_{l \in L: l \neq m_i} c x_{il}}_{(a)} + \underbrace{\sum_{l \in L} u \kappa_l}_{(b)} + \underbrace{\sum_{l \in L} b \delta_l}_{(c)} \tag{1}$$

s.a.

$$\sum_{i \in I} \omega_{il} + k_l - \delta_l = \overline{r_l} \qquad \forall l \in L \tag{2}$$

$$\sum_{l \in L} \omega_{il} = h \qquad \forall i \in I \tag{3}$$

$$\omega_{il} \leq h x_{il} \qquad \forall i \in I, l \in L \tag{4}$$

$$x_{il} = 1 \qquad \forall i \in I, l \in L : l = m_i \tag{5}$$

$$v_i = \sum_{i \in L: l \neq m_i} x_{il} \qquad \forall i \in I \tag{6}$$

$$\sum_{i \in I_l} v_i = \sum_{i \in \{I - I_l\}} x_{il} \qquad \forall l \in L \tag{7}$$

$$x_{il} \in \{0,1\} \qquad \forall i \in I, l \in L \tag{8}$$

$$v_i \geq 0 \qquad \forall i \in I \tag{9}$$

$$\omega_{il} \geq 0 \qquad \forall i \in I, l \in L \tag{10}$$

$$\kappa_l, \delta_l \geq 0 \qquad \forall l \in L \tag{11}$$

La función objetivo (1) minimiza los siguientes costos semanales: (a) capacitación de empleados en departamentos adicionales; (b) subdotación; y (c) sobredotación. Las restricciones (2) explican el cumplimiento de la demanda, y nos permiten calcular el nivel de sobre/subdotación de personal asociado con cada departamento. Las restricciones (3) aseguran que los empleados trabajen exactamente la cantidad de horas requeridas por su contrato. Las restricciones (4) imponen que cada empleado pueda ser asignado a trabajar en, y solo en, departamentos para los que han sido capacitados. Las restricciones (5) determinan el departamento para el que se capacitó originalmente a cada empleado. Las restricciones (6) indican, para cada empleado, cuántas habilidades tiene

en total. Las restricciones (7) garantizan para cada departamento *l*, que exista igualdad entre la cantidad de habilidades adicionales de los empleados propios que son entrenados para trabajar en otro departamento de la tienda $\left(\sum_{i\in I_l} v_i\right)$ y la cantidad de empleados pertenecientes a otros departamentos que recíprocamente fueron entrenados para trabajar en el departamento l $\left(\sum_{i\in\{I-I_l\}} x_{il}\right)$; estas restricciones garantizan la formación de cadenas cerradas (CLC y / o CSC). Finalmente, las restricciones (8) - (11) definen el dominio de cada variable.

4.2 Formulación estocástica de dos etapas

Esta subsección presenta una reformulación del modelo determinístico presentado en la Subsección 4.1 a un modelo de programación estocástica a dos etapas (TSSO) considerando demanda estocástica. En esta formulación hay variables de primera y de segunda etapa. Las variables de la primera etapa, x_{il} y v_i están relacionadas con las decisiones sobre capacitar a los empleados en diferentes departamentos. Las variables de la segunda etapa, $\omega_{il}(s), \kappa_l(s),$ y $\delta_l(s),$ son los ajustes operativos que se hacen una vez se observa la demanda incierta en cada departamento. Es decir, una vez conocida las realizaciones de la demanda, pueden producirse sobredotación o subdotación de personal.

A continuación, presentamos la versión TSSO de la formulación (1) - (11), usando el método comúnmente conocido como *Sample Average Approximation* (SAA) [28].

$$Min \quad \underbrace{\sum_{i\in I}\sum_{l\in L:l\neq m_i} cx_{il}}_{primera-etapa} + \underbrace{\frac{1}{|S|}\left[\sum_{s\in S}\sum_{l\in L} u\kappa_l(s) + \sum_{s\in S}\sum_{l\in L} b\delta_l(s)\right]}_{segunda-etapa} \tag{12}$$

s.a.

$$\sum_{i\in I} \omega_{il}(s) + k_l(s) - \delta_l(s) = \overline{r}_l(s) \qquad \forall l \in L, s \in S \tag{13}$$

$$\sum_{l\in L} \omega_{il}(s) = h \qquad \forall i \in I, s \in S \tag{14}$$

$$\omega_{il}(s) \leq h x_{il} \qquad \forall i \in I, l \in L, s \in S \tag{15}$$

$$x_{il} = 1 \qquad \forall i \in I, l \in L : l = m_i \tag{16}$$

$$v_i = \sum_{i\in L:l\neq m_i} x_{il} \qquad \forall i \in I \tag{17}$$

$$\sum_{i\in l_l} v_i = \sum_{i\in\{I-I_l\}} x_{il} \qquad \forall l \in L \tag{18}$$

$$x_{il} \in \{0,1\} \qquad \forall i \in I, l \in L \tag{19}$$

$$v_i \geq 0 \qquad \forall i \in I \tag{20}$$

$$\omega_{il}(s) \geq 0 \qquad \forall i \in I, l \in L, s \in S \tag{21}$$

$$\kappa_l(s), \delta_l(s) \geq 0 \qquad \forall l \in L, s \in S \tag{22}$$

La función objetivo (12) busca minimizar el costo de capacitación semanal (decisiones de la primera etapa) y el costo semanal esperado de sobre/subdotación de personal (decisiones de la segunda etapa). En la versión de TSSO, las decisiones sobre cuáles empleados serán capacitados en dos o más departamentos, están asociadas a la primera etapa del problema estocástico. Estas decisiones afectarán los niveles de sobre/subdotación de personal; los cuales son decisiones asociadas a la segunda etapa del problema. Por lo tanto, el objetivo en el enfoque TSSO es elegir las variables de la primera etapa que minimizan la suma de los costos de la primera etapa y el valor esperado de los costos de la segunda etapa.

Con respecto a las restricciones (2) - (11) presentadas en la formulación determinista, las restricciones (2) - (4) y (10) - (11) se modificaron para incorporar explícitamente la incertidumbre de la demanda. Tenga en cuenta que todas estas restricciones implican solo variables de segunda etapa. Por lo tanto, las restricciones (5) - (9) no recibieron ninguna modificación porque están asociadas con variables de primera etapa. Además, tenga en cuenta que la interpretación de las restricciones (13) - (22) y las restricciones (2) - (11) es la misma.

A diferencia de la formulación (4.1), la formulación (4.2) incorpora explícitamente la incertidumbre en la demanda. Esto permite que las decisiones sobre la polifuncionalidad sean factibles y robustas ante perturbaciones en la demanda pronosticada. Finalmente, esto implica que la formulación determinista (4.1) puede inducir a una inadecuada planificación del personal y a mayores costos laborales.

5 Caso de estudio

5.1 Requerimientos de datos

Esta subsección describe las características y la configuración de los conjuntos y parámetros utilizados en este estudio. La base de datos utilizada contiene datos reales y simulados, que se deriva de una tienda de retail ubicada en Santiago de Chile. A continuación, presentamos una descripción de ambos conjuntos de datos.

Datos reales. El caso de estudio considera una tienda con 6 departamentos y 30 empleados, es decir, $|L| = 6$ y $|I| = 30$. Todos los empleados tienen el mismo contrato, tal que todos los empleados deben trabajar 45 horas por semana, es decir, $h = 45$. Para el departamento 1 (D1), $\overline{r}_1 = 315$ (es decir, 7 empleados) mientras que para los otros 5 departamentos: (D2), $\overline{r}_2 = 225$; (D3), $\overline{r}_3 = 135$; (D4), $\overline{r}_4 = 135$; (D5), $\overline{r}_5 = 180$ y (D6), $\overline{r}_6 = 360$. En cuanto a los parámetros de costo, asumimos un costo mínimo de capacitación por empleado $(c = US\$1 - sem/empleado)$ [29]. Los costos asociados con la sobredotación y subdotación de personal son iguales a $u = US\$60/h$ y $b = US\$15/h$, respectivamente.

Datos simulados. Se consideran dos tipos de datos simulados asociados a la demanda incierta, estos son: (i) datos dentro de la muestra (*in-sample*) y (ii) datos fuera de la muestra (*out-of-sample*). Los datos dentro de la muestra se refieren a los datos iniciales que se utilizarán para encontrar las soluciones a las variables de primera etapa usando

el enfoque TSSO. Mientras que los datos fuera de la muestra se refieren a los datos que se reservarán para comparar el rendimiento de las soluciones generadas por el enfoque de optimización TSSO y los enfoques miopes: Polifuncionalidad Cero (PC) y Polifuncionalidad Total (PT). El enfoque miope PC representa un experimento donde todos los empleados se mantienen como especialistas y, por lo tanto, no hay empleados polifuncionales. El enfoque miope PT representa un experimento donde todos los empleados serán polifuncionales y pueden trabajar en cualquier departamento de la tienda.

En ambos tipos de datos simulados, y con el objetivo de evaluar cómo funcionan las estructuras de polifuncionalidad con el enfoque *k-chaining* con $k \geq 2$ y diferentes niveles de incertidumbre, nosotros consideramos nueve niveles de variabilidad para la demanda en cada departamento de la tienda: $CV = 5, 10, 20, 30, 40, 50, 60, 70, 80\%$.

Para ambos conjuntos de datos, se considera que las realizaciones no negativas de la demanda estocástica para cada departamento de la tienda siguen una distribución normal, y para evitar generar valores de demanda atípicos las funciones de distribución de probabilidad se truncan en los percentiles 5 y 95 (es decir, representamos el 90% de la distribución de datos). Para los parámetros aleatorios de las horas semanales de demanda $r_i(s)$, utilizamos una simulación de Monte Carlo para generar aleatoriamente $|S| = 1000$ y $|S| = 10000$ escenarios para los datos dentro y fuera de la muestra respectivamente.

6 Resultados y discusión

6.1 Análisis dentro de la muestra

Los resultados y las discusiones de este análisis se dividen en las siguientes dos subsecciones: Tiempos computacionales y tamaño de los modelos, y ¿Cuánta polifuncionalidad se debe agregar?

Tiempos computacionales y tamaño de los modelos. El modelo TSSO (12) – (22) se escribió en AMPL y el problema se resolvió utilizando el software comercial CPLEX que se ejecuta a través de NEOS server durante 8 h (restrictivo). Para cada CV, el enfoque TSSO se ejecutó considerando 1000 realizaciones de la demanda en cada uno de los 6 departamentos de la tienda.

La Tabla 2, para cada CV, informa los tiempos computacionales obtenidos por el enfoque TSSO (en horas) y el modelo determinista (DT) (en segundos). A su vez, la tabla muestra el tamaño de los modelos. En general, los tiempos de solución del enfoque TSSO son mucho más altos como resultado de la diferencia en el tamaño de los modelos. Cabe aclarar que debido a que las decisiones abordadas en este estudio son a nivel estratégico con un horizonte de planificación semanal los tiempos que arroja el modelo TSSO se consideran razonables. Adicionalmente, considerando todos los CV, nosotros reportamos que los gaps de optimalidad con el enfoque TSSO fueron menores al 0,05%.

Tabla 2. Tiempos computacionales y tamaño de los modelos

	Tiempo en CPU								Tiempo promedio	Restricciones	Variables binarias	Variables continuas
	5%	10%	20%	30%	50%	60%	70%	80%				
TSSO	1,18	8	8	8	6,3	8	8	8	6,935	216066	150	192060
DT	1,48								1,48	282	150	252

¿Cuánta polifuncionalidad se debe agregar? El objetivo en esta subsección es responder a la siguiente pregunta táctica: ¿Cuántos empleados deben ser polifuncionales y en cuántos departamentos adicionales? Dado este propósito, determinamos el número óptimo de empleados polifuncionales requeridos para cada departamento y nivel de variabilidad en la demanda (CV). En la Figura 3 se muestra (en colores) el número óptimo de empleados polifuncionales por departamento y CV, y se incluyen las siguientes cuatro métricas. Primera, el porcentaje de empleados polifuncionales en relación con el número total de empleados, %EP. Segunda, el porcentaje de empleados polifuncionales entrenados en un departamento adicional y, por lo cual, capacitados en un total de dos departamentos, %EP(2). Tercera, el porcentaje de empleados polifuncionales entrenados en dos departamentos adicionales y, por lo cual, capacitados en un total de tres departamentos, %EP(3). Cuarta, el porcentaje de polifuncionalidad total (%PT), que se refiere al número de habilidades adicionales capacitadas, en relación con el número máximo teórico factible.

		Demanda media						%EP	%EP(2)	%EP(3)	%PT
		315	225	135	135	180	360				
	5	1	1	1	1	1	1	20	20	0	4
	10	2	1	1	1	1	2	27	27	0	5
	20	3	2	1	1	2	3	40	40	0	8
	30	4	3	2	2	2	5	60	60	0	12
%CV	40	5	4	2	2	3	6	73	73	0	15
	50	6	4	3	3	4	7	90	90	0	18
	60	7	5	3	3	4	8	100	90	10	22
	70	7	5	3	3	4	8	100	70	30	26
	80	7	5	3	3	4	8	100	63	37	27
		D1	D2	D3	D4	D5	D6				
		Departamento									

Figura 3. Métricas de polifuncionales asociadas a cada nivel de variabilidad en la demanda.

La figura muestra como la cantidad de empleados polifuncionales de la tienda aumenta a medida que aumenta el valor de la demanda media de un departamento y el nivel de variabilidad (CV). También se observa que cuando la variabilidad es la más baja (CV=5%), solo se requiere un empleado polifuncional por departamento a pesar del supuesto de costo mínimo de capacitación. Este resultado puede interpretarse como la inversión mínima necesaria en polifuncionalidad (es decir, EP = 20% y PT = 4%). A su vez, cuando la variabilidad de la demanda es la más alta (CV=80%), el número óptimo de empleados polifuncionales por departamento es igual a su personal total. De hecho, para CVs iguales o mayores al 60% se requiere que el 100% de los empleados sean polifuncionales.

Por otro lado, se puede notar que para un CV del 5% al 50% el total de empleados polifuncionales está capacitado en un total de dos departamentos (es decir, un departamento adicional). Esto indica que para estos escenarios de variabilidad en la demanda una política *2-chainning* entrega el máximo beneficio. Sin embargo, para altos niveles de variabilidad en la demanda, CV= 60,70 y 80%, se requieren empleados polifuncionales capacitados en uno o hasta en dos departamentos adicionales. Por lo tanto, para ningún CV se requieren empleados polifuncionales entrenados en tres o más departamentos adicionales (es decir, 4 o más departamentos en total). Esto indica que valores de k=2 y k=3 en las políticas *k-chaining* ofrecen los resultados más costo-efectivos.

Adicionalmente, para cada CV, la Figura 4 presenta de forma detallada la cantidad de empleados polifuncionales en la tienda que están entrenados en un total de dos departamentos o tres departamentos.

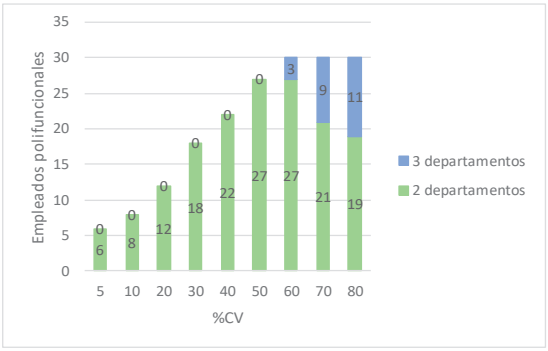

Figura 4. Número de empleados polifuncionales en dos o tres departamentos para cada CV.

6.2 Análisis fuera de la muestra

El objetivo en esta subsección es hacer comparaciones justas entre las soluciones del enfoque TSSO y los enfoques miopes PT y PC. La Tabla 3 presenta para cada combinación, de enfoque y CV, los valores de las métricas asociadas a los análisis dentro y fuera de la muestra. Las columnas 2,3,4 y 5 muestran los requerimientos de polifuncionalidad entregados en el análisis dentro de la muestra (es decir, %EP, %EP(2), %EP(3) %PT) y reportados en la Figura 3. Las columnas 6 y 7 están asociados al análisis fuera de la muestra, los cuales se basan en los 10000 escenarios de demanda generados a través de la simulación Monte Carlo. La columna 6 muestra el porcentaje de ahorro en el costo semanal promedio de sobre/subdotación de personal ($\%\overline{SSA}$) que se obtiene para cada enfoque. La columna 7 reporta el costo total semanal promedio incurrido $(\overline{\varphi})$ en cada enfoque.

Note que, la métrica $\%\overline{SSA}$ permite evaluar la fiabilidad y robustez de las soluciones entregadas por cada enfoque. Por un lado, el enfoque miope PT siempre exhibirá la mayor fiabilidad y robustez posible, es decir, logra la máxima reducción posible en el costo semanal de sobre/subdotación de personal ($\%\overline{SSA} = 100$). Sin embargo, es el enfoque más conservador, pues exige la inversión máxima en polifuncionalidad (%EP =%PT = 100%). Por el contrario, el enfoque miope PC siempre reporta el costo total

promedio más alto, debido a que no proporciona ningún nivel de protección ante la variabilidad de la demanda (es decir, %ME =%TM = $\%\overline{SSA}$ = 0%.). Respecto al enfoque TSSO, al igual que el enfoque PT, este también logra el máximo ahorro en el costo semanal de sobre/subdotación de personal ($\%\overline{SSA}$ = 100) para cada CV, pero con una inversión mucho menor en polifuncionalidad. Por lo tanto, el enfoque TSSO siendo menos conservador que el enfoque PT, logra para cada CV el costo total promedio más bajo. Este resultado es muy interesante, pues mediante el enfoque TSSO con *k-chaining*, se cosecha el 100% de los beneficios potenciales alcanzables, pero con una inversión mucho menor, lo cual lo hace rentable y atractivo para los tomadores de decisión.

Tabla 3. Métricas de desempeño para cada enfoque y CV

Enfoque	Métricas						Enfoque	Métricas					
	dentro de la muestra				fuera de la muestra			dentro de la muestra				fuera de la muestra	
	%EP	%EP(2)	%EP(3)	%PT	$\%\overline{SSA}$	$\bar{\varphi}$ (US$)		%EP	%EP(2)	%EP(3)	%PT	$\%\overline{SSA}$	$\bar{\varphi}$ (US$)
	CV=5%							CV=10%					
TSSO	20	20	0	4	100	709	TSSO	27	27	0	5	100	1426
PT	100	-	-	100	100	853	PT	100	-	-	100	100	1565
PC	0	-	-	0	0	1670	PC	0	-	-	0	0	3337
	CV=20%							CV=30%					
TSSO	40	40	0	8	100	2811	TSSO	60	60	0	12	100	4213
PT	100	-	-	100	100	2948	PT	100	-	-	100	100	4344
PC	0	-	-	0	0	6640	PC	0	-	-	0	0	9936
	CV=40%							CV=50%					
TSSO	73	73	0	15	100	5574	TSSO	90	90	0	18	100	7084
PT	100	-	-	100	100	5698	PT	100	-	-	100	100	7199
PC	0	-	-	0	0	13246	PC	0	-	-	0	0	16654
	CV=60%							CV=70%					
TSSO	100	90	10	22	100	8356	TSSO	100	70	30	26	100	10623
PT	100	-	-	100	100	8460	PT	100	-	-	100	100	10720
PC	0	-	-	0	0	19859	PC	0	-	-	0	0	23342
	CV=80%												
TSSO	100	63	37	27	100	12945							
PT	100	-	-	100	100	13028							
PC	0	-	-	0	0	26636							

7 Conclusiones y futura investigación

Este estudio presenta una nueva versión del problema semanal de asignación de personal polifuncional con encadenamiento y demanda incierta. Nuestros resultados brindan una base para construir políticas de polifuncionalidad que respondan a dos preguntas fundamentales: cuánta y cómo agregarla. Respecto a la primera pregunta, los resultados mostraron que incluso cuando el costo de capacitación es mínimo no se necesita la polifuncionalidad total para asegurar los máximos beneficios de la polifuncionalidad. Además, que el número de empleados polifuncionales requeridos aumenta a medida que la demanda media de un departamento y el coeficiente de variación de la demanda son mayores. Para la segunda pregunta, los resultados mostraron que la mejor forma de agregar polifuncionalidad es generar estructuras de personal que combinen personal especializado y personal polifuncional.

Por otro lado, los resultados nos ayudan a concluir que el enfoque TSSO exhibe excelentes rendimientos al lograr el 100% de los beneficios potenciales de la polifuncionalidad total, pero con una inversión menor. También los resultados demuestran que, para escenarios de variabilidad de la demanda menores o iguales al 50%, una política *2-chainning* reporta los máximos beneficios posibles. Pero con niveles de variabilidad mayores al 50% se requiere de mayores niveles de polifuncionalidad, por lo cual en estos escenarios es más beneficioso el uso de políticas *k-chainning* con $k \geq 2$. Sin embargo, en nuestro caso de estudio, se encontró que no se necesitan empleados polifuncionales que estén capacitados en más de tres departamentos para conseguir los beneficios máximos.

En cuanto a la investigación futura, los nuevos estudios pueden relajar algunos de nuestros supuestos. Por lo tanto, la metodología podría modificarse para: (1) Evaluar una política de flexibilidad que considere simultáneamente decisiones de polifuncionalidad y contratación de personal. (2) Considerar que los empleados son heterogéneos, es decir, que la productividad individual de cada uno pueda variar dependiendo de la cantidad de departamentos en los cuales se encuentre capacitado. (3) Permitir que los costos de sobredotación, subdotación y capacitación varíen de un departamento a otro.

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Aplicações da Simulação de Monte Carlo em problemas de Programação Linear: uma revisão sistemática da literatura

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Resumo. A incerteza está presente na maioria dos processos produtivos. Estimar a demanda, gerenciar os recursos e preparar-se para enfrentar os riscos inerentes às oscilações de mercado é fundamental para a permanência da empresa no cenário competitivo atual. Nos últimos anos, a comunidade científica tem demonstrado interesse nos aspectos relacionados à previsão do comportamento de parâmetros estocásticos em sistemas de otimização. Desta forma, a fim de perceber a importância que pesquisadores e periódicos dão ao assunto e quais as áreas de maior aplicação, escolheu-se, como método de pesquisa, a Revisão Sistemática de Literatura. A partir disso, como objetivo geral da pesquisa, buscou-se compreender como a Simulação de Monte Carlo (SMC), incorporada à Programação Linear (PL), pode contribuir na percepção e incorporação da variabilidade nos processos de produção. Foram identificados 113 artigos, publicados entre 2015 e 2019, os quais foram analisados a fim de estimar em que problemas essas ferramentas são mais utilizadas. Também foi identificado como se dá a compreensão dos fenômenos produzidos pela aleatoriedade e que ferramentas podem ser incorporadas ao processo de otimização visando uma compreensão mais abrangente. Por fim, a análise dos artigos selecionados revelou que as áreas que mais utilizam a SMC incorporada à PL estão relacionadas às pesquisas em energia renovável e sustentabilidade.

Palavras-chave: Incerteza· Simulação de Monte Carlo· Programação Linear· Revisão de Literatura.

1 Introdução

A reconfiguração do mercado econômico, estimulada pela globalização, determina que as instituições adaptem suas estratégias de gestão a fim de que possam manter a competitividade. A adoção de novas tecnologias nos processos produtivos e a modernização das ferramentas de gestão podem ser a base para a consolidação das empresas nos panoramas nacional e internacional [1–5].

Na teoria econômica a instituição é considerada uma unidade produtiva que atua na transformação de insumos em bens e serviços. A necessidade da atualização e

otimização de procedimentos objetiva a manutenção financeira e a provisão de lucros, consecutivamente há o crescimento da empresa no mercado [6].

Contudo, as incertezas de demanda futura, de preços de mercado, de recursos disponíveis e a necessidade de redução dos custos operacionais motiva as instituições quanto à busca do equilíbrio econômico-financeiro [7–10]. A atenção dos pesquisadores e especialistas está voltada à incorporação de novos modelos de produção a fim de otimizar processos, minimizando perdas e maximizando lucros [4, 11, 12].

Entretanto, a sensibilização por melhorias não está restrita à eficiência econômica. Ela também abrange os aspectos ambientais e sociais. Prever o comportamento incerto dos recursos naturais, a emissão de poluentes e as questões relacionadas à saúde e ao bem-estar passaram a integrar às responsabilidades dos gestores no momento da tomada de decisão [13–16].

Corroborando com o exposto, no campo da engenharia a empresa é uma unidade técnica que executa processos de transformação. Embora seja caracterizada quantitativamente como um conjunto de parâmetros e coeficientes, a instituição permeia as relações entre o material, o humano e o energético, sendo um dependente do outro [6].

Nesta perspectiva, a Pesquisa Operacional (PO) pode ser utilizada como apoio nos processos decisórios. Por meio de modelos matemáticos é possível simular e avaliar problemas reais de forma criteriosa, considerando os principais parâmetros e suas influências nos sistemas, sejam eles simples ou robustos. As técnicas de otimização auxiliam o tomador de decisão no controle das variáveis do projeto e na administração dos recursos disponíveis [5, 17–19].

Diante do exposto, o objetivo desta pesquisa é explorar o uso da Simulação de Monte Carlo (SMC) como ferramenta de avaliação da incerteza e variabilidade em problemas de Programação Linear (PL). Por meio de revisão sistemática de literatura, pretende-se verificar quais são as situações em que essa ferramenta está sendo empregada, além de apurar seus benefícios e limitações.

Este artigo está estruturado em cinco seções. Na segunda seção, será realizada a contextualização teórica acerca do tema. Na sequência, a terceira seção apresentará a estratégia de busca e de seleção dos artigos para compor o banco de dados. A quarta seção constituirá na análise e apresentação das pesquisas que utilizaram SMC para avaliar a aleatoriedade em suas situações-problema. Serão discutidos os resultados decorrentes das observações na quinta seção para que na sexta, e última seção, possam ser apresentadas as considerações finais e perspectivas sobre pesquisas futuras.

2 Referencial Teórico

2.1 Pesquisa Operacional

A PO surgiu durante a Segunda Guerra Mundial, a partir da necessidade de encontrar solução para problemas militares de ordem logística, estratégica e tática. À época, cientistas foram convocados para estudar situações relacionadas à otimização dos escassos recursos disponíveis [17, 18, 20, 21].

Em 1947, George Bernard Dantzig e sua equipe formularam e resolveram um Problema de PL para a Força Aérea Militar norte americana. Os estudos realizados pela

equipe de Dantzig embasaram-se nas pesquisas do matemático russo Kantorovich e proporcionaram o desenvolvimento do Algoritmo Simplex, de considerável relevância nos problemas de otimização atuais [5, 18, 22].

Os métodos e as ferramentas da PO tratam tanto os modelos determinísticos quanto os estocásticos. Os primeiros possuem parâmetros constantes e conhecidos e são resolvidos por meio de sistema de equações; e os modelos estocásticos, que retratam a maioria dos problemas reais de PO, apresentam a incerteza agregada a um ou mais parâmetros. Neste último caso, são encontradas mais do que uma solução, sem a obrigatoriedade de definir a ótima [17, 20, 23].

Além da escolha da ferramenta ideal, que é balizada pela complexidade de cada problema, os especialistas podem executar os modelos com o auxílio de pacotes de otimização e/ou softwares auxiliares. Para a resolução de Problemas Lineares, Não Lineares ou variações, os pacotes de otimização mais conhecidos são: CPLEX®, LINDO®, LINGO®, OSL®, XPRESS®. Já os softwares utilizados são: GAMS®, @Risk®, AMPL®, RStudio® entre outros [18].

2.2 Programação Linear

A PL é um dos métodos da PO mais utilizados na otimização de problemas e tem por objetivo dar suporte à tomada de decisão seja ela estratégica, tática ou operacional. O modelo é expresso por uma função linear: a função objetivo, de forma que a cada função objetivo sejam atribuídas condições operacionais, também chamadas de restrições [17, 20, 21, 23].

O modelo geral de PL [17, 18], utilizado para otimizar a função objetivo, pode ser representado como segue :

Otimizar:

$$Z = \sum_{j=1}^{n} c_j x_j \qquad (1)$$

sujeito a:

$$\sum_{j=1}^{n} a_{ij} x_j \geq b_i \qquad i = 1, 2, \dots, p \qquad (2)$$

$$\sum_{j=1}^{n} a_{ij} x_j = b_i \qquad i = p+1, p+2, \dots, m \qquad (3)$$

$$x_j \geq 0, \; j = 1,2, \dots, n \qquad (4)$$

$$x_j \in \Re, \; j = q+1, q+2, \dots, q+n \qquad (5)$$

sendo:

A = $\{a_{ij}\}$ é a matriz de restrições e a_j equivale à j-ésima coluna de A;

x = (x_j) e c = (c_j), ambos com j ∈ N são vetores coluna e linha de n componentes, respectivamente;

d = (d_i) com i ∈ M é vetor coluna de m componentes;

M = {1, 2, ..., m} é o conjunto dos índices das restrições do problema e;

N = {1, 2, ..., n} o conjunto dos índices das variáveis.

Após a construção do modelo matemático, o qual representa o problema de PL, é possível determinar a solução ótima. Para isso, podem ser utilizados diversos algoritmos, o mais antigo e ainda mais usual é o Algoritmo Simplex. Vários são os setores que aplicam a PL para a otimização de problemas, entre eles estão o rodoviário, naval, industrial, saúde, comércio, energia, entre outros [18, 24–27].

A PL pode ser utilizada tanto para modelos determinísticos quanto estocásticos.

Embora os modelos determinísticos sejam mais fáceis de tratar em virtude da precisão de seus parâmetros, nem sempre refletem a realidade. Em decorrência disso, prevendo a variabilidade dos parâmetros no decorrer de um processo, considera-se mais efetiva a utilização dos modelos estocásticos [13, 16, 28–30].

Nesse sentido, quando há a variabilidade dos parâmetros de um sistema, é necessário que seja adotada alguma ferramenta de simulação ou previsão da aleatoriedade. A SMC pode ser efetiva para a composição do modelo e a previsão dos riscos e incertezas [31–33].

2.3 Simulação De Monte Carlo (SMC)

A SMC é uma ferramenta confiável para estimativa de incertezas. É frequentemente utilizada na física, matemática e engenharia, especificamente na análise de probabilidade e estatística em virtude da alta precisão e simplicidade na representação da aleatoriedade [7, 33, 34].

Os algoritmos fundamentados na SMC são exibidos como valores intervalares, usualmente apresentados como funções de distribuição de probabilidades (FDPs). A representação aleatória pode ser obtida por meio de tabelas ou softwares específicos e o processo ocorre a partir de iterações que resultam em um conjunto de distribuição de resultados [32, 35–37].

Para tratar as incertezas identificadas nos problemas que surgem tanto dentro da indústria quanto no mercado de serviços, podem ser utilizadas inúmeras abordagens. Contudo, a SMC aliada aos algoritmos da PL estão entre as mais usuais quando é necessário realizar uma avaliação criteriosa de procedimentos operacionais mais complexos [28, 38, 39].

Esta técnica permite a análise do comportamento estocástico das variáveis de input e a compreensão das variáveis de output. Cada vez mais utilizada em virtude do aprimoramento computacional, a SMC assegura que as incertezas e os riscos estarão incorporados na análise de todos os cenários possíveis e na tomada de decisão [5, 40, 41].

3 Materiais e Métodos

Caracterizada como teórico-conceitual [42], esta pesquisa objetiva a busca e seleção de artigos publicados entre 2015 e julho 2019 para a coleta de dados sobre a aplicabilidade da SMC em problemas de PL (PPL). Por meio desta pesquisa bibliográfica [43], pretende-se verificar o que já foi produzido pela comunidade científica sobre a temática, apontar lacunas e delinear pesquisas futuras.

Esta pesquisa pode ser considerada exploratória e descritiva, pois por meio da seleção de artigos em bases de dados, previamente selecionadas, pretende-se a construção do conhecimento e a posterior apresentação do portifólio encontrado. Quanto à abordagem, este trabalho pode ser enquadrado como quali-quantitativo devido aos processos de seleção, análise e quantificação das produções científicas [44].

Como protocolo de pesquisa foi utilizado o Método *Preferred Reporting Items for Systematic review and Meta-Analysis Protocols* (PRISMA-P), na tradução literal Principais Itens para Relatar Revisões sistemáticas e Meta-análises. Esta metodologia

consiste em 17 passos destinados a facilitar a organização e elaboração da Revisão Sistemática de Literatura (RSL) e se caracteriza por ser um método íntegro e transparente, que exige justificativa, hipótese e etapas bem definidas [45].

O processo de revisão teve início com a delimitação do problema de pesquisa qual seja, buscar a aplicabilidade da SMC em PPLs. A partir disso, utilizando as palavras-chave "Monte Carlo" e "Linear Programming", procedeu-se a busca por artigos publicados em periódicos de língua inglesa, nas bases *Thomson Reuters Web-of-Science (WoS)*, *Scopus*, *ScienceDirect*, *Emerald Insight* e *SciELO*, por meio do Portal de Periódicos da Capes.

Após o retorno das bases citadas, foram adotadas as seguintes etapas para a elegibilidade dos artigos: (i) excluir os trabalhos duplicados; (ii) excluir os textos que não se caracterizavam como artigos; (iii) excluir artigos que não contemplavam o tema proposto, a partir da leitura do título e do resumo; e (iv) após procedida a leitura completa, houve a exclusão dos artigos não compatíveis com o objetivo desta revisão.

Visando proporcionar uma compreensão mais abrangente do tema e observar as lacunas existentes na literatura, buscou-se extrair dos artigos inclusos no banco de dados, os seguintes elementos: título, ano de publicação, autor(es), periódico, países de origem da publicação, número de citações, objetivo, área em que o tema pertence, ferramentas utilizadas, contribuições, limitações da pesquisa e indicação de trabalhos futuros.

Por fim, o objeto deste estudo consiste na análise, compreensão e apresentação da produção científica selecionada, no apontamento da relevância do conhecimento gerado, na descrição de possíveis dificuldades e resultados e na indicação de tendências de pesquisa neste campo de estudo.

4 Resultados

A partir da busca nas bases selecionadas, foram encontradas 2.592 publicações com as palavras-chave "Monte Carlo" e "Linear Programming". Destas, 123 (4,7%) provinham da base *Thomson Reuters Web-of-Science (WoS)*, 182 (7%) da base *Scopus*, 2.210 (85,3%) da base *ScienceDirect*, 77 (3%) da base *Emerald Insight* e nenhuma publicação foi encontrada na base *SciELO* para o período de 2015 a julho de 2019.

As produções encontradas foram organizadas no software Mendeley®. Esse aplicativo computacional possui ferramentas úteis para o gerenciamento de referências bibliográficas, tais como categorização por pastas, exclusão de arquivos duplicados e suporte à construção de referências na redação de textos.

Nas primeira e segunda etapas foram excluídos, respectivamente, 81 textos duplicados e 463 trabalhos que não se encaixavam na classificação de artigos publicados em periódicos. Desta forma, 2.038 (78,6%) artigos receberam a atenção quanto à leitura do título e resumo. Foi necessário analisar esses dois elementos conjuntamente em razão de que alguns textos não mencionavam os termos de busca no título, contudo somavam na literatura pretendida nesta revisão.

A partir disso, foram selecionados 194 artigos para a revisão integral do texto, dos quais 113 passaram a compor o banco de dados desta Revisão. As publicações estão distribuídas entre 59 periódicos, sendo que os de maior destaque foram: *European Journal of Operational Research* com 12 artigos, *Energy* com 10, *Applied Energy* com 9 e *Journal of Cleaner Production* com 8 artigos.

Em relação às áreas de concentração dos periódicos, observou-se que 21 (35,6%) destinam-se a publicações referentes à conservação do meio ambiente, eficiência energética e sustentabilidade. Contudo, notou-se que além destes, outros 8 periódicos que tem como alvo publicações diversas, também apresentam artigos contemplando esses assuntos. Desta forma, 64 artigos (56,6%) estão relacionados ao mesmo tema.

Quanto aos anos de publicação dos trabalhos, vale ressaltar que o interesse dos autores quanto ao uso da SMC em PPLs é crescente, conforme ilustra a Figura 1. Isto se deve, também, à modernização dos equipamentos de informática que são ferramentas indispensáveis para a previsão de demandas sobre incerteza quando são necessárias milhares de simulações.

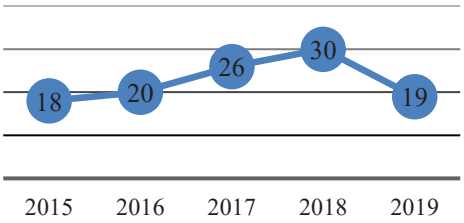

Fig. 1. Distribuição percentual do número de publicações por ano (Fonte: Elaboração própria).

Os 337 autores estão distribuídos entre 37 países, destacando os Estados Unidos com 54 autores, a China com 48 e o Irã com 30 autores. Os países de mais destaque estão relacionados na Figura 2.

Foi identificada a distribuição por continente dos autores para mensurar a intensidade de interesse pelo tema nas diferentes partes do mundo. Desta forma, pode-se observar que a Europa e a Ásia são as regiões em que se concentram a maior parte das publicações com 36% e 35%, respectivamente. Na sequência, o Continente Americano traz 25% das publicações e por fim, a Oceania e a África contribuem com 2% dos artigos cada uma.

Os principais autores têm origem no continente asiático, como percebe-se na Tabela 1. Os três primeiros autores pertencem a um grupo de pesquisa da China e os últimos dois autores são de um grupo de pesquisa das Filipinas. Ambos os grupos se dedicam ao planejamento de sistemas de energia e de abastecimento de água sob incerteza, ao estudo de redes de gerenciamento de carbono, visando a redução da emissão de CO_2 e à implementação de sistemas híbridos de energia.

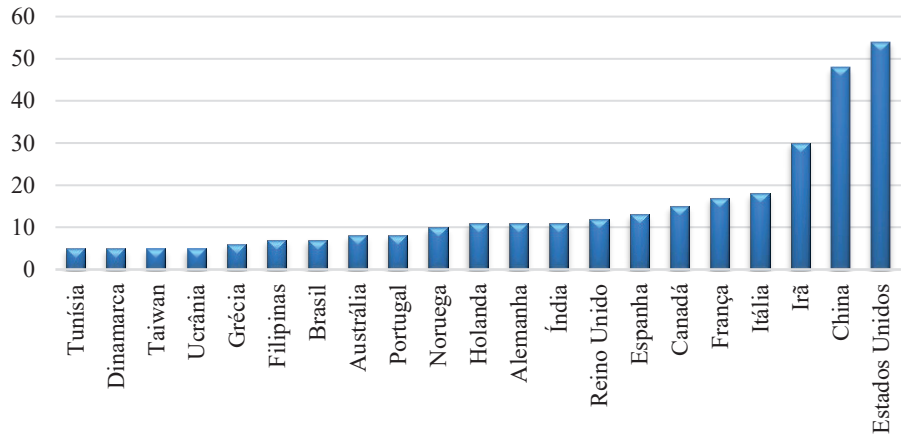

Fig. 2. Distribuição percentual do número de autores por país (Fonte: Elaboração própria)

Autor	Quantidade de artigos	País
Y. P. Li	6	China
L. Yu	5	China
G.H. Huang	5	China
Kathleen B. Aviso	5	Filipinas
Raymond R. Tan	5	Filipinas

Tabela 1. Principais autores (Fonte: Elaboração própria).

5 Discussão

O tratamento da aleatoriedade de parâmetros em problemas de otimização tem sido foco dos pesquisadores de programação matemática nos últimos cinco anos. Ademais, aliada a esta temática surgiu o termo "otimização robusta", o qual se refere a um conjunto de ferramentas com capacidade suficiente de prover resultados em modelos com algum tipo de incerteza [39, 46, 47].

A SMC é amplamente utilizada para avaliar o comportamento incerto de variáveis sobre um determinado problema. Este método contempla sorteios de algarismos pertencentes a determinada distribuição de probabilidades, com base no comportamento prévio das variáveis em certo período [8, 48–50]. Desta forma, organizam-se os diversos cenários que serão analisados a fim de avaliar a sensibilidade do sistema em virtude da aleatoriedade presente nas variáveis [51].

Quase que a totalidade dos problemas identificados nesta revisão utilizou a SMC conjunta à Programação Linear Inteira (PLI) ou Programação Linear Inteira Mista (PLIM) devido à complexidade de seus problemas. O que as diferencia é a caracterização das variáveis e a robustez do

problema. Na PL as variáveis são contínuas, na PLI as variáveis são discretas e a PLIM contempla tanto variáveis discretas quanto contínuas [18].

Marques et *al.* [30] utilizou a SMC integrada à PLIM com o objetivo de integrar decisões estratégicas para o lançamento de produtos farmacêuticos. A técnica se mostrou eficaz tanto na captura dos efeitos da incerteza no sistema quanto no embasamento de decisões acerca da produção, transporte e lançamento dos produtos. Foi possível quantificar os riscos e os ganhos inerentes ao projeto, favorecendo a tomada de decisão.

Wang e Yujie [52] utilizaram a SMC para simular a localização individual de trabalhadores residentes em Baton Rouge - Louisiana e seus empregos. O objetivo foi quantificar o excesso de deslocamento a fim de otimizar o tempo dos funcionários. A metodologia proposta se mostrou favorável ao objetivo do estudo, contudo se fosse aplicada a uma cidade maior, a pesquisa enfrentaria limitações computacionais devido ao tamanho da amostra e o tempo necessário para as simulações. Neste caso, seria necessário agregar mais ferramentas para a resolução.

Com base na análise do comportamento de todos os parâmetros do sistema, fundamental no estudo de problemas de programação, é possível prever quais são as ações necessárias e possíveis para suprir determinada demanda. Exemplificando, Dai e Zheng [53] utilizaram o algoritmo genético híbrido embutido na SMC, a programação *fuzzy* e a programação com restrições de probabilidade para gerenciar uma cadeia fechada de suprimentos (*Closed-loop Supply Chain*).

Não obstante às necessidades de otimizar os recursos visando aumentar os lucros, a empresa que pretende permanecer no cenário econômico atual precisa operar de forma sustentável, socialmente e ambientalmente responsável. Neste ínterim, as preocupações com emissão de poluentes, captação de recursos naturais e descarte de possíveis dejetos de produção estão inseridas no contexto da organização [16, 54–57].

Neste sentido, Jareonkitpoolpol et *al.* [58] propôs o uso de PL, programação com restrição de chance (PRC) e SMC como ferramentas para determinar a fórmula ideal de um fertilizante orgânico-químico. O objetivo do estudo foi produzir um produto que proporcionasse a redução de resíduos químicos no solo e minimizasse o custo final atendendo aos padrões de qualidade, além de reduzir o volume de importações de substâncias químicas.

Khalilzadeh e Derikvand [1] apresentaram um modelo de seleção de fornecedores para uma cadeia de suprimentos considerando o custo total das peças, a qualidade dos itens fornecidos e o nível de emissão de gases de efeito estufa do fornecedor. Neste problema a incerteza é abordada pela programação estocástica e o modelo de múltiplos objetivos é resolvido com base na PL.

Utilizando a PL e a SMC, Tallentire et *al.* [59] propõe a redução nos impactos ambientais decorrentes da produção e consumo de alimentos que abastecem a cadeia produtiva de frangos de corte. O objetivo da pesquisa foi desenvolver uma ferramenta para a formulação de dietas para os animais, projetada para atingir e reduzir categorias de impacto ambiental específicas em duas regiões contrastantes, o Reino Unido e os EUA.

Diante disso, as relações que uma empresa precisa estabelecer com seus fornecedores e clientes, sobre as responsabilidades ambiental e social, não podem ficar restritas aos seus colaboradores e às suas operações. É exigido que os gestores reflitam sobre ações de médio e longo prazo que promovam o fortalecimento da empresa no panorama da sustentabilidade e adotem estratégias para a valorização não somente do lucro, mas também das pessoas e do planeta, conforme prevê a abordagem *triple-botton-line* [13].

No campo da geração de energia, as preocupações não se registram apenas quanto a satisfação da demanda pelo menor custo, mas também na diminuição do impacto ambiental do processo de

geração. Desta forma, Ioannou et *al.* [50] construiu um método de otimização estocástica em vários estágios para determinar o mix ótimo de geração de energia de médio a longo prazo. As incertezas na demanda de energia, nos preços de combustíveis e no custo das tecnologias aplicadas são previstas utilizando a SMC.

Em virtude das alterações naturais provocadas pelo aquecimento global, a atenção de muitos pesquisadores se voltou para o estudo da eficiência no fornecimento de energia limpa, ou seja, com baixa emissão de carbono. Neste sentido, a SMC contribui para a previsão da velocidade dos ventos, da temperatura e demais variáveis que podem influenciar na provisão desta demanda [38, 60–64].

No decorrer desta pesquisa foram quantificadas outras ferramentas que vêm sendo aplicadas na resolução de Problemas de PL, PLI e PLIM a fim de diminuir o tempo computacional, de melhor construir o modelo ou de analisar o sistema com mais precisão. Identificou-se o uso de números *fuzzy* [19, 53, 65, 66], de cadeias de Markov [13, 67], de técnicas de inteligência computacional como algoritmos genéticos [68] e enxame de partículas [69, 70], de metodologias multicritério de apoio à decisão como a Análise Envoltória de Dados (DEA) [71], entre outros.

6 Considerações finais

A partir da reestruturação do comércio e do aumento das relações provocadas pela internacionalização de produtos e serviços, as instituições vêm encontrando novos desafios para manter a competitividade. É crescente a busca pela eficiência na produção, pela adoção de novas tecnologias e pela adequação às exigências do mercado [30, 47, 71, 72]. Além disso, vinculada à questão econômico-financeira está a preocupação com a saúde [24, 56], os recursos naturais [7, 73], a sustentabilidade [59, 74] e a eficiência energética [38, 61, 75].

De forma geral, a SMC é um dos métodos mais simples para prever e tratar as incertezas e associada à PL, contribui para que os recursos possam ser previstos e otimizados. No entanto, os cálculos são mais lentos e exigem maior esforço computacional, uma vez que é necessário contabilizar milhares de observações até chegar ao resultado. Isso corrobora para que sejam indicados métodos híbridos de tratamento da incerteza [8, 15, 49, 71, 76].

Entre os artigos analisados, várias ferramentas foram associadas à SMC na intenção de diminuir o tempo de cálculo como os Métodos Multicritério de Apoio à Decisão [5, 71, 77], os algoritmos genéticos [53], métodos de análise de sensibilidade local e global [51] entre outros.

A partir da escolha de otimização de um recurso específico, sugere-se que seja realizada a comparação de diferentes métodos de tratamento de incertezas, avaliando a precisão e a carga computacional utilizada em cada método.

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2D Nesting and Scheduling in Metal Additive Manufacturing

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Abstract. Additive manufacturing (or 3D printing) is considered to be the future of manufacturing. Flexibility, accuracy, rapidness, cost efficiency and lightness are among the advantages those additive manufacturing provides. Astronauts can now produce their own tools and parts in the space with no waiting for another launch. Planning of additive manufacturing machines is a recent hot topic. Efficient use of such resources plays an important role to reduce the costs of additively manufactured parts as well as disseminate this technology making its advantages more apparent. This research addresses the metal additive manufacturing machine scheduling problem with multiple unidentical selective laser melting machines. Machines may have different specifications (dimension, speed, and cost parameters) and parts may have different characteristics (width, length, height, volume, release date and due date). The objective is to obtain a schedule such that total tardiness is minimized and parts are allocated on platforms (or building trays) with no overlap. A genetic algorithm approach is proposed to solve the problem within reasonable times. Results of the computational tests show the promising performance of the proposed method.

Keywords: Metal Additive Manufacturing, 3D Printing, Scheduling, 2D Nesting, Production Planning.

1 Introduction

The manufacturing industry has faced an enormous advancement with the utilization of additive manufacturing (or 3D printing) technologies. *Selective laser melting (SLM)*, *selective laser sintering*, *fused deposition modelling*, *electronic beam melting* and *stereolithography* are some of the most popular ones belonging to this technology. Different from traditional manufacturing techniques which subtract material to produce a final product, 3D printing technologies produce 3D objects through a layer-by-layer production process [1].

Additive manufacturing provides several advantages as opposed to conventional subtractive techniques. Design flexibility, high accuracy, resource efficiency, lightness,

strength and material efficiency are some of those advantages. However, design flexibility is probably the most important one among them. This is because, additive manufacturing allows very complex design structures with the flexibility of layer-by-layer production. With the shift from rapid prototyping to direct digital manufacturing, this feature helps to position additive manufacturing in a higher technology level.

SLM is used to melt and fuse metallic powders together via a high-power density laser. The powder is very fine and deposited on a substrate using a roller with a thickness of usually between 20 μm and 100 μm. The high-power density laser beam melts the 2D cross section of the first layer and so fuses those areas. Afterwards, a new layer of powder is deposited on the substrate and corresponding areas are melted and fused via laser. This layer-by-layer process is repeated until a final product is achieved [2].

The application areas of SLM technique, especially for titanium alloys, are expanding even more recently. SLM has become a widely used additive manufacturing technique to fabricate critical parts (such as turbopumps) used in aerospace. NASA has decided to additively manufacture a rocket engine fuel pump in one piece instead of mounting hundreds of components (including a turbine that spins at over 90,000 rpm) [3]. So that the additively manufactured pump has 45% fewer parts in comparison with traditionally manufactured pumps [1].

The increase in the wide application of AM technologies and demand on 3D printed parts force companies use their resources more efficiently. In this context, considerations for planning and scheduling of additive manufacturing resources are gaining more importance. This research proposes a genetic algorithm (GA) approach to efficiently schedule multiple AM machines for fabricating part orders coming from several customers with the aim of minimizing total tardiness. 2D nesting of parts on the machine platforms (building bed) are also considered as a constraint. Machines are unidentical; their speed, capacity and cost parameters are different. Parts have different dimensions, volume, due dates and release dates. As a unique contribution to literature, this is the first study, which minimizes total tardiness considering 2D nesting of parts, in AM machine scheduling domain.

The remainder of this paper is organized as follows. The following section reviews the literature. Section 3 describes the problem characteristics. Section 4 provides the basic steps of the proposed GA approach. Section 5 reports the results of computational tests and finally Section 6 concludes the paper with future research directions.

2 Literature Review

While the literature on AM and 3D printing is rather extensive, the number of studies on planning and scheduling of AM machines is quite limited. This section reviews the literature on planning and scheduling of AM machines and shows the gap in the literature.

AM machine scheduling problem was introduced by Kucukkoc et al. [4]. They addressed the characteristics of planning production on AM machines and proposed a mathematical formulation to calculate job production times. The model proposed by Kucukkoc et al. [4] aims at increasing the utilization of additive manufacturing

machines considering order delivery times. Another preliminary work on production planning of AM machines belongs to Li et al. [5]. They proposed a mathematical model and two heuristics (i.e. best-fit and adapted best-fit algorithms) to minimize average production cost per volume of material. Following this, the topic attracted many researches. Chergui et al. [6] addressed nesting and scheduling in additive manufacturing. They proposed a mathematical formulation and a heuristic to satisfy demands by customers considering due dates. Kucukkoc et al. [7] proposed a GA approach to minimize maximum lateness in a multiple AM machine environment. Fera et al. [8] developed a modified GA approach for time and cost optimization of single AM machine scheduling problem. Dvorak et al. [9] proposed heuristics for scheduling AM machines considering due dates. Kucukkoc [1] proposed mixed-integer linear programming models to minimize makespan in single, parallel identical and parallel non-identical AM machine scheduling problems. Li et al. [10] introduced the dynamic order acceptance and scheduling problem and proposed a strategy-based metaheuristic decision-making approach. The proposed approach helps companies decide whether to accept an order and when to produce it on which machine.

This survey shows that there is no research in metal additive manufacturing field that minimizes total tardiness while considering 2D nesting constraints. Thus, this paper contributes to literature proposing a GA approach to minimize total tardiness while ensuring 2D nesting feasibility.

3 Problem Definition

As clearly described by Kucukkoc [1], the problem of production planning and scheduling of metal AM machines is NP-Hard to solve. A group of AM machines in different specifications (i.e. width, length, speed, etc.) are available to produce parts received from individual customers. The parts also have different characteristics (i.e. width, length, height, volume, and due date) which need to be taken into account to obtain a feasible and efficient solution. The problem is to group parts into batches (called jobs) and allocate them to machines such that a performance criterion is optimized. The performance criterion aimed in this research is total tardiness minimization.

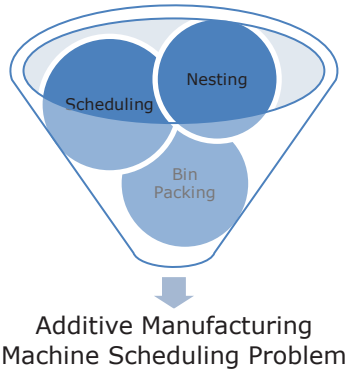

Fig. 1. Three basic components of the AM machine scheduling problem.

Although the problem can be supposed to be a classical bin packing problem, actually it is not. This is a multi-faced problem which involves many different problems inside: *bin packing*, *scheduling* and *nesting* (see Fig. 1). Furthermore, grouping parts and assigning them to machines can be considered a *batch scheduling* problem. However, Kucukkoc [1] shows why this problem cannot be considered as a batch scheduling problem.

Fig. 2 depicts a schematic representation of the addressed problem in an environment with multiple AM machines of SLM type. The two questions which need to be answered are as follows:

- Which parts will be grouped together into which job batch?
- Which job batch will be processed when and on which machine?

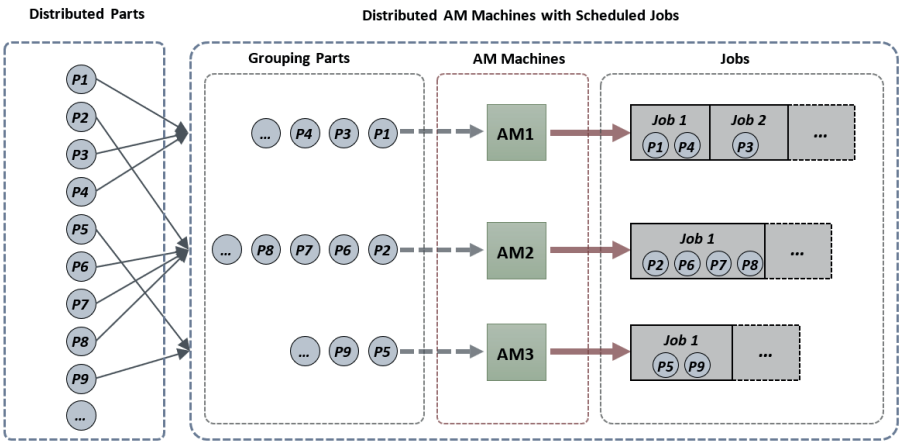

Fig. 2. A schematic representation of the multiple AM machine scheduling problem [1].

One can suppose that there is a two-stage decision making process. However, the parts are grouped as a job batch considering not only other parts in the same job, but also the specifications of the machine that job will be fabricated on. Therefore, these two questions are tightly interrelated to each other and the solution process cannot be divided into two consecutive stages. The problem must be handled through a holistic view.

Another complicated feature of this problem is that the processing times of jobs are dynamically calculated via a formula. That means the processing times are not known before the content of the job is not decided. For example, in a classical batch scheduling problem, the maximum processing time of a part in a batch determines the processing time of that batch. However, in a metal AM scheduling problem, the processing time of a job (or batch) is calculated via a formula (see Eq. (1)) considering the maximum height and total volume of the parts assigned to that job.

Each part ($i \in I$) has a width (w_i), length (l_i), height (h_i), area (a_i), volume (v_i), release date (r_i) and due date (d_i). Each machine ($m \in M$) has a maximum width (MW_m), length (ML_m), height (MH_m) and area (MA_m) supported by its tray or building platform. Machines also have other parameters, i.e. VT_m, HT_m, and SET_m. These

parameters are used for calculating job processing times and costs. VT_m is the time spent to form per unit volume of material. HT_m is the time spent for powder-layering (it is repeated for each layer based on the highest part produced in the job). SET_m is the set-up time needed for initialising and cleaning before/after each job. Eq. (1) is used to calculate the production time of a job ($j \in J$) on a machine (m).

$$PT_{mj} = SET_m \cdot Z_{mj} + VT_m \cdot \sum_{i \in I} v_i \cdot X_{mji} + HT_m \cdot \max_{i \in I}\{h_i \cdot X_{mji}\} \quad (1)$$

where X_{mji} and Z_{mj} are binary variables. X_{mji} is equal to 1 if part i is assigned to job j on machine m, otherwise it is 0. Z_{mj} is equal to 1 if job j on machine m is utilized; 0, otherwise. A job is considered to be utilized if at least one part is assigned to that job.

As seen in Eq. (1), PT_{mj} is the sum of three terms: (i) set-up time, (ii) material releasing time (based on total volume) and (iii) powder layering time (based on maximum height). This equation indicates that different combinations and allocations of same parts on to different machines yield different processing times and so completion times of parts. Therefore, grouping parts with similar heights may provide an advantage in reducing the processing time of a job.

The completion time of a job on a machine (CT_{mj}) can be stated as in Eq. (2).

$$CT_{mj} \geq ST_{mj} + PT_{mj} \quad \forall m \in M, j \in J. \quad (2)$$

where ST_{mj} is the start time of job j on machine m. A job can start when all parts in this job are ready to be built and no part can be removed until *all* parts in the job are completed. Therefore, the start time of a job (ST_{mj}) must be greater than or equal to the maximum of release dates in that job, i.e. $ST_{mj} \geq \max_{i \in I_{mj}}\{r_i\}$ where I_{mj} denotes the set of parts assigned to job j on machine m. Considering the basic assumption of processing one job at a time on a machine, it is necessary to start a job after the completion of a previous job on that machine ($ST_{mj} \geq CT_{m,j-1}$). Therefore, the start time of a job can be expressed as in Eq. (3), where $CT_{m0} = 0$.

$$ST_{mj} \geq \max\left\{CT_{m,j-1}, \max_{i \in I_{mj}}\{r_i\}\right\} \quad \forall m \in M, j > 1. \quad (3)$$

The completion time of a part (C_i) is equal to the completion time of job in which this part is assigned; $C_{i \in I_{mj}} = CT_{mj}$. Thus, the tardiness of a part (T_i) can simply be calculated as $T_i = \max\{0, C_i - d_i\}$. Thus, the objective function is to minimize the total tardiness $T = \sum_i T_i$.

A 2D nesting problem occurs to ensure a feasible allocation of parts into job batches. One can assume that it is enough to satisfy that the sum of part areas does not exceed the building area capacity of the machine's platform. However, there is a chance that this assumption can yield infeasible solutions when the parts are physically located on the machine platform. Therefore, a 2D nesting problem has also been combined with the machine scheduling problem in this research.

Basic assumptions of the problem are given as follows:

- The maximum capacity (width, length and height) of at least one machine is large enough to fabricate the largest part in terms of width, length and height.
- Part specifications are known and deterministic.
- Machine specifications are known and deterministic.
- Machines may have different capacity and specifications.
- No breakdowns or failures.
- Only one job can be processed on a machine at any time.
- All parts need to be assigned to a job exactly once.
- No parts can be added to a job after the job starts.
- A part can be removed from a job after all parts have been completed in the same job.
- All machines are available at the start of planning period.
- Building orientations of parts are known and constant.
- 2D nesting problem is considered to ensure that the allocations do not exceed machines' width and length.

Under these assumptions, the problem is to find the optimum allocation of parts to jobs on machines such that the total tardiness is minimized. Following section presents the proposed GA based approach with numerical examples.

4 Proposed Method

The problem studied here is neither a classical machine scheduling problem nor a nesting problem itself. Therefore, a sophisticated solution method is necessary to obtain efficient as well as high-quality solutions.

In this research, the GA approach proposed by Kucukkoc et al. [4] is modified to minimize total tardiness considering the 2D nesting constraints. The pseudocode of the proposed GA approach is given in Fig. 3.

```
GA
1    Generate initial population
2    Evaluate chromosomes in the population (considering 2D
     nesting constraints)
3    WHILE (no improvement in the last MaxItNoImp iterations)
4        Tournament selection
5        Genetic operators (Crossover & Mutation)
6        Evaluate newly generated chromosomes
7        Form new generation (replace the worst in the popula-
         tion)
8    ENDWHILE
9    Stop and report the best solution
```

Fig. 3. Pseudocode of the proposed GA approach.

The algorithm starts with generating random chromosomes to assure diversity. Fig. 3 presents the pseudocode of the proposed GA approach. The number of chromosomes in the population is constant. After generating the population, each chromosome in the population is evaluated using the procedure given in Fig. 4 considering the nesting constraints. Parents are selected using tournament selection (given in Fig. 5) and genetic operators are applied. The procedures used for crossover and mutation are given in Fig. 6 and Fig. 7, respectively. After crossover and mutation, the newly obtained individuals (children) are evaluated using the same decoding procedure and the new population is formed replacing the worst chromosomes with a better child (if any). Each chromosome is made up of part numbers (or IDs) generated with permutation coding. So that, each gene represents a part number and each part is represented on the chromosome only once. Therefore, the length of a chromosome equals the number of parts to be produced. If there are 8 parts, a sample chromosome could be `chrom={3,8,4,1,7,2,6,5}`. The order of parts on the chromosomes are used in the decoding procedure. Parts are selected one by one based on their sequence on the chromosome and allocated to jobs on machines based on the decoding procedure provided in Fig. 4 (where `AP` denotes the list of parts not assigned and `nm` is the number of machines).

Decoding Procedure

```
1    Add all parts into set AP in the order that they appear on
     the chromosome
2    Set j ← 1 //job index
3    WHILE (AP ≠ ∅)
4      FOR (m = 1 TO nm STEP 1) //start from the first machine
5        totArea ← 0, I_mj ← ∅
6        FOREACH (i in AP) //try each part
7          IF (totArea + a_i ≤ MA_m and h_i ≤ MH_m and w_i ≤ MW_m and
           l_i ≤ ML_m)
8            IF (totArea = 0 or Nesting(i, I_mj) = true)
9              Add part i to I_mj
10             totArea ← totArea + a_i
11             Remove part i from AP
12           ENDIF
13         ENDIF
14       ENDFOREACH
15       j ← j + 1
16     ENDFOR
17   ENDWHILE
18   return
```

Fig. 4. Pseudocode of the decoding procedure.

In the decoding procedure, nesting constraints are satisfied via an external function, called `Nesting()`, for which the source code can be retrieved from GitHub [11]. This function gets a machine ID and a list of parts as parameter and returns true if they fit on the machine tray with no exceedance. The algorithm starts with the first machine and first job. The first part on the chromosome is selected and checked if it fits on the tray. If the part's width, length, height and area are smaller than or equal to the machine's width, length, height and area, the first phase of the control process is completed. In the second phase of the control process, the machine ID and part's data is sent to the `Nesting()` function together with existing parts list in the same job on the same machine. If the returned result is true, the part is assigned to the current job and the `totArea` is increased by a_i. If the result is false, the next part is checked following the same procedure. When no more part can be allocated to a job, the machine ID is altered and the unallocated parts are tried to be assigned after a two-stage feasibility control process. When all the machines are full, new jobs are opened and the assignment process continues starting from the first machine again. This cycle continues until all parts have been allocated. As seen from this procedure, a two-stage control process is utilized to check the assignment feasibility of a part to a job on a machine and the nesting condition is checked if the first stage is completed successfully. This is because `Nesting()` function has a time consuming procedure and it is called only when the first phase of the control is completed successfully. So that any unnecessary nesting efforts are avoided.

The parents for genetic operators are selected using a tournament selection procedure given in Fig. 5. To determine two parents, the procedure is applied twice and the winners are designated as parents. The tournament size (`tourSize`) is determined as `Ceil(popSize/6)`, where `Ceil(X)` returns the smallest integral value that is greater than or equal to `X`. So that the diversity is ensured and chromosomes with better fitness values have more chance for reproduction. However, all individuals have a chance to be selected.

Selection (Tournament)

```
1    Set min ← MAX_Value, winner ← ∅, tourSize ← Ceil(popSize/6)
2    FOR (t = 1 TO tourSize STEP 1)
3      Choose a random chromosome (p) from the population
4      IF (Fitness(p) < min)
5        Set winner ← p
6      ENDIF
7    ENDFOR
8    return
```

Fig. 5. The procedure used for tournament selection.

Winners of the tournament selection (`parent1` and `parent2`) undergo crossover and mutation, respectively. Crossover helps mostly better chromosomes generate new

individuals and form next generations. It is applied via determining a random cut point (`cp`) and systematically combining the genes of the two parents referencing that cut point (see Fig. 6). The head of `child1` is retrieved from the first part of `parent1` (from the first gene to `cp`). The remaining genes of `child1` is completed based on the sequence of missing genes after `cp` on `parent2`. Similarly, the head of `child2` is the head of `parent2` (from the first gene to `cp`) and the remaining part (`tail2`) of `child2` is completed based on the order of missing genes after `cp` on `parent1`. So that, one crossover is completed. This is repeated several times based on a parameter called `crossover rate` whose value is determined by the user.

Crossover

```
1   cp ← [1, chromSize] //Determine a random cut point (cp)
2   Initialise child1 and child2; child1 ← ∅, child2 ← ∅
3   head1 ← parent1[1, cp]; head2 ← parent2[1, cp]
4   temp1 ← parent1[cp + 1, chromSize] + parent1[1, cp]
5   temp2 ← parent2[cp + 1, chromSize] + parent2[1, cp]
6   Set tail1 ← ∅, tail2 ← ∅
7   FOREACH (i in temp2) //Build tail1
8     IF (i ∉ head1)
9       Add part i to tail1
10    ENDIF
11  ENDFOREACH
12  FOREACH (i in temp1) //Build tail2
13    IF (i ∉ head2)
14      Add part i to tail2
15    ENDIF
16  ENDFOREACH
17  child1 ← head1 + tail1, child2 ← head2 + tail2
18  return
```

Fig. 6. The procedure used for crossover.

Mutation is another important genetic operator. It helps algorithm scan different areas of the search space and prevents algorithm stuck in local optima. Fig. 7 shows the procedure used for mutation. A parent is selected from the population via tournament selection and either `swap` or `insert` is applied based on the value (between [0,1]) of a random variable, i.e. `rand`. The two randomly determined genes are swapped and a mutant is constituted if the random variable is lower than 0.5. If not, a randomly determined gene is moved to another randomly determined location to obtain a `mutant`.

Mutation rate controls how many times mutation will be applied on a newly selected parent.

```
Mutation
    rand ← Random[0,1] //to determine swap or insert
    r1 ← Random[1, chromSize] //determine a random location r1
    r2 ← Random[1, chromSize] //determine a random location r2
    WHILE (r1 = r2)
      r2 ← Random[1, chromSize]
    ENDWILE
    IF (rand < 0.5) //swap operation
      temp ← parent[r1]
      parent[r1] ← parent[r2]
      parent[r2]] ← temp
    ENDIF
    IF (rand ≥ 0.5) //insert operation
      Move part at r1 to its new location r2 on parent
    ENDIF
    return
```

Fig. 7. The procedure used for mutation.

New generation is formed replacing the worst chromosomes in the population with the best individuals (children) obtained from genetic operators. In this process, it is very important to avoid duplication of chromosomes. Otherwise, a couple of iterations later the population may be just a multiple copy of the same chromosome.

The algorithm runs until there is no improvement in a predefined number of iterations and the best solution is reported.

5 Tests and Results

The proposed GA approach has been coded in JAVA and run on Intel® Core™ i7-6700HQ CPU @2.60 GHz with 16 GB of RAM to solve the test problems given in Table 1. Number of parts (*nbParts*), number of machines (*nbMachines*), range of parts, and machines used to fabricate parts are provided for each test instance. For example, I6 is constituted of 14 parts (i.e. P15-P28 in part dataset) and three SLM machines (two of which are M1 and the other one is of M2). Test problems have been organized in ascending order of their complexity. The problem complexity increases when the number of parts and the number of machines get larger. Machine park has been differentiated to obtain a more diversified problem set. Details of SLM machine specifications

are obtained from Kucukkoc [1] and provided in Table 2. Part dataset is also provided in Table A1 (see Appendix).

The population size, crossover rate and mutation rate are considered to be 30, 0.6 and 0.1, respectively. The algorithm was terminated when there is no improvement within 2500 iterations for test instances I1-I6 and 5000 iterations for test instances I7-I20. The values of these parameters have been determined through some preliminary tests considering the problem size [7].

Table 1. Data on test instances.

Test Instance	nbParts	nbMachines	Range of Parts	Machines
I1	12	2	P1-P12	M1[1], M2[1]
I2	12	2	P13-P24	M1[1], M2[1]
I3	14	2	P1-P14	M1[1], M2[1]
I4	14	2	P15-P28	M1[1], M2[1]
I5	14	3	P1-P14	M1[1], M2[2]
I6	14	3	P15-P28	M1[2], M2[1]
I7	18	2	P1-P18	M1[1], M2[1]
I8	18	2	P11-P28	M1[1], M2[1]
I9	18	2	P15-P32	M1[1], M2[1]
I10	18	3	P19-P36	M1[2], M2[1]
I11	24	3	P1-P24	M1[2], M2[1]
I12	24	3	P1-P24	M1[1], M2[2]
I13	24	4	P17-P40	M1[2], M2[2]
I14	24	5	P17-P40	M1[3], M2[2]
I15	30	5	P1-P30	M1[3], M2[2]
I16	30	6	P1-P30	M1[3], M2[3]
I17	30	7	P11-P40	M1[4], M2[3]
I18	30	8	P11-P40	M1[4], M2[4]
I19	40	11	P1-P40	M1[6], M2[5]
I20	40	12	P1-P40	M1[6], M2[6]

Table 2. Machine specifications.

Machine ID	Height (cm)	Width (cm)	Length (cm)	Area (cm^2)	Set-up Time (hr)	HT (hour/cm)	VT (hour/cm^3)
M1	32.5	25	25	625	2.00	1	0.030864
M2	32.5	25	25	625	1.00	1	0.030864

The results of the experimental tests have been reported in Table 3. The column *nbJobs* indicates the total number of jobs utilized on machines. While the ultimate goal of the GA is to minimize *total tardiness*; *maximum tardiness* and *the number of late parts* are also reported as additional performance indicators. Moreover, the time consumed to

solve each problem has been reported in seconds (s) for the comparison purposes in future researches.

The GA algorithm finds reasonable solutions within short CPU times. The CPU time requirement increases with the increase in the number of parts and so the problem complexity. This is because of the exponential increase in the search space. Each problem has been solved three consecutive times and the best results are reported.

When the results are investigated, some problems have no tardiness. See, for example, I1, I5-I7 and I10. That means no part is late in these cases. In I3 and I5, the same parts (i.e. P1-P14) are scheduled with a different machine park. For I3, there is only one machine in each type (M1 and M2). So, this problem is solved with a total of two machines. However, for I5, there are three machines in total (two machines of type M2 and one M1) which yields a better fitness value (0 instead of 18.57) as expected. The maximum of objective value was observed for I8 with a total tardiness of 335.08 hr.

Table 3. Results of the experimental tests.

Test Instance	nbJobs	Maximum Tardiness (hr)	Number of Late Parts	Total Tardiness (hr)	CPU(s)
I1	5	0	0	0	31
I2	6	57.89	2	66.43	39
I3	6	10.35	2	18.57	62
I4	6	56.58	3	98.55	46
I5	5	0	0	0	66
I6	6	0	0	0	52
I7	8	0	0	0	142
I8	7	135.44	5	335.08	118
I9	8	97.12	7	308.61	89
I10	9	0	0	0	100
I11	9	10.22	1	10.22	183
I12	9	7.54	1	7.54	172
I13	9	114.30	3	213.50	175
I14	10	34.84	2	36.92	231
I15	12	28.19	2	38.36	432
I16	11	26.21	3	58.16	321
I17	13	110.64	5	174.66	225
I18	12	94.06	3	139.80	339
I19	15	62.46	6	148.56	386
I20	15	76.52	3	152.44	586

A part of the convergence graph of the proposed GA approach is given in Fig. 8 for I12 where total tardiness is ‘7.54’. As seen from the graph, the best fitness value in the initial population was over 1000 hr of total tardiness. GA produces efficient schedules which gradually decreases total tardiness to ‘7.54’ in the first 500 iterations.

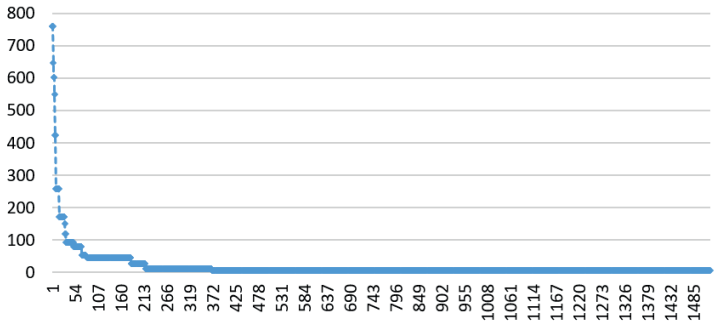

Fig. 8. Convergence of the proposed algorithm (the first section)

The detailed nesting result of the best solution for I12 is also provided in Fig. 9. It is worthy to note here that the nesting function is used just to make sure that the assigned parts to a job do not exceed the dimensions of the tray, not to maximize the utilization of the trays. This is because minimization of the *nbJobs* does not mean the minimization of the total tardiness as contextualized in previous sections.

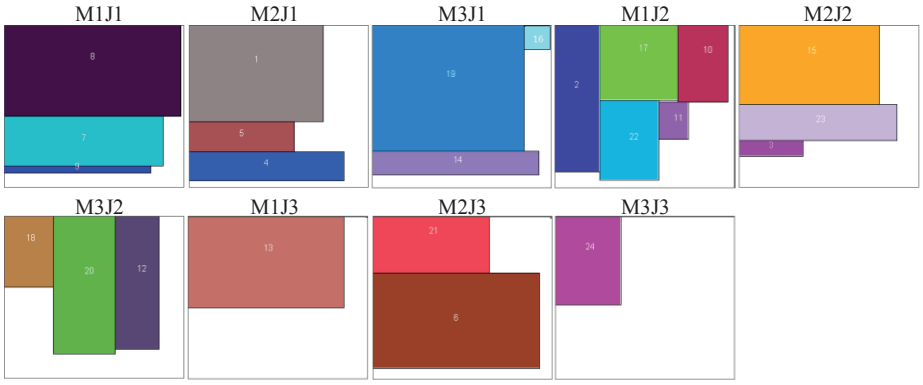

Fig. 9. Allocation of parts to jobs.

6 Conclusions and Future Research

This paper proposed a GA approach for scheduling metal additive manufacturing machines to minimize total tardiness considering 2D nesting constraints in a multiple unrelated parallel machine environment. The proposed method employs a nesting function which ensures that the parts assigned to a job on a machine do not exceed tray capacity (in terms of width and length) as well as height. The production time of a job is calculated via a function based on the content of the job, i.e. the maximum height and total volume of parts assigned to that job. Pseudocodes of GA mechanisms have been provided and test problems have been solved. Test data is given in details to provide comparable data in future researches. The results reported exhibits the promising solution

building capacity and convergence of the proposed approach. However, as the problem is new and there is no comparable result reported in the literature, the performance of the proposed GA has not been compared to another method.

In future studies, new metaheuristics (e.g. ant colony, tabu search, bee colony etc.) can be developed to solve the test instances provided in this paper and results can be compared to that of GA reported in this paper. The capacity of the proposed GA can also be improved with some problem specific genetic operators. Furthermore, fabrication of irregular shaped parts on multiple SLM machines can be considered as an original research topic for future works.

Appendix

Table A1. Part dataset used for test problems.

Part	h_i	w_i	l_i	a_i	v_i	r_i	d_i
P1	16.7	18.8	16.0	300.8	1573.8	6.25	305.90
P2	8.8	6.7	22.8	152.8	421.3	7.35	282.18
P3	20.3	9.3	2.1	19.5	147.8	9.83	378.25
P4	7.4	21.6	3.9	84.2	285.2	20.95	214.67
P5	27.3	14.9	4.1	61.1	583.3	36.58	148.98
P6	25.8	23.2	12.9	299.3	3282.5	51.50	576.18
P7	14.5	22.2	6.7	148.7	1265.5	56.35	240.42
P8	3.5	24.6	15.3	376.4	723.3	69.90	211.63
P9	20.4	20.5	1.0	20.5	278.5	75.07	330.87
P10	23.3	6.8	13.4	91.1	1051.8	86.00	387.98
P11	26.3	4.0	5.0	20.0	201.9	93.03	447.13
P12	12.8	5.9	21.0	123.9	866.1	93.10	445.10
P13	28.4	21.8	15.3	333.5	7347.6	97.15	634.57
P14	10.9	23.2	3.2	74.2	333.6	97.25	177.55
P15	14.1	19.6	13.7	268.5	2956.0	101.75	355.30
P16	3.9	3.6	3.1	11.2	32.5	106.95	258.75
P17	3.2	10.6	13.1	138.9	265.6	107.58	295.55
P18	24.6	7.3	12.6	92.0	1387.4	115.55	509.62
P19	7.1	21.2	20.0	424.0	1086.0	128.37	294.25
P20	25.2	8.4	21.6	181.4	3559.2	132.32	575.72
P21	29.6	16.4	10.6	173.8	2902.9	134.15	569.97
P22	21.1	10.8	8.0	86.4	854.6	136.65	353.23
P23	25.2	22.0	4.9	107.8	1986.0	138.30	326.28
P24	28.2	9.5	14.9	141.6	2974.3	149.48	515.72
P25	22.9	6.3	4.6	29.0	408.2	164.08	525.87
P26	24.2	17.7	9.4	166.4	1271.4	167.45	362.63
P27	19.0	1.0	20.9	20.9	252.4	177.23	358.03
P28	26.6	11.2	19.7	220.6	3740.9	206.40	589.43
P29	18.5	12.5	8.2	102.5	991.9	219.62	560.93
P30	10.1	15.4	11.9	183.3	1377.6	228.55	653.97
P31	24.5	24.5	24.2	592.9	11122.9	242.90	1177.72
P32	30.6	23.0	11.9	273.7	5234.1	244.87	739.32

P33	3.1	14.7	9.9	145.5	274.6	245.08	553.43
P34	18.9	17.4	14.8	257.5	2628.4	248.18	536.87
P35	11.2	1.7	23.9	40.6	206.9	258.98	524.58
P36	4.6	19.5	10.4	202.8	639.5	268.42	646.72
P37	23.4	2.6	15.9	41.3	431.5	279.77	691.40
P38	7.5	13.7	18.5	253.5	968.2	286.25	566.03
P39	12.7	8.2	1.4	11.5	95.0	290.73	335.78
P40	22.7	14.3	12.5	178.8	2306.2	294.53	473.53

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A Genetic Algorithm for Flexible Job Shop Scheduling Problem with Scarce Cross Trained Setup Operators*

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Abstract. Many researchers developed algorithms for a dual-resource constrained flexible job shop (DRC-FJSP) where both machines and workers need to be simultaneously scheduled. In those models and algorithms in the literature, the authors assumed that workers are machine operators responsible for performing the production process steps from the beginning to the end of the operation. However, because of increased automation and the adoption of numerically controlled machines, workers become machine tenders and should not be bottleneck and constraining resources. On the other hand, skilled setup operators remain being constraining limited resources in industries. Unlike machine tenders, a setup operator can leave the machine once setup is completed and take on another setup operation on another machine. In this paper, for the first time, we develop a genetic algorithm for a new DRC-FJSP where setup operators and machine tools are constraining resources. Numerical examples of varying problem sizes are presented to show the performance of the algorithm.

Keywords: Flexible Job-shop Scheduling; Dual Resource Constrained; Scarce Setup Operators; Detached setup; Genetic Algorithm.

1 Introduction

Flexible job-shop scheduling problem (FJSSP) is an expansion of the job shop scheduling problem (JSSP), which is one of the combinatorial optimization problems considered to be NP-hard [5, 2, 3]. The consideration of machines and the human resource component in the scheduling environment is known as a Double-Resource, or Dual-Resource constrained (DRC) system. Systems centered around human resources are viewed across literature under DRC, where the degree of versatility and workforce assignment could affect the system's performance [6]. Dual-resource constrained systems are more complex than their counterparts, single resource costrined (SRC), and they pose extra challenges that need to be addressed during resource scheduling [14]. The primary aim of human-resource

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scheduling in DRC systems is to have the right amount of eligible people to perform the required task at the right time. Human operators that are not cross-trained cannot address situations where there are unexpected work-orders and unbalanced workloads [9, 8]. While the DRC systems' efficiency increases with workers' versatility [1]; however, according to [7], having a workforce system that is fully cross-trained may not be attainable due to the high cost of training. Previous studies have been scheduling workers as operators whose duty is to operate the machines with no experience or training on machine setups. It is assumed that this category of machine operators can be acquired at low cost (i.e., cheap labor that can be hired and fired at will). Also, the machine operators must stay and tend the assigned machines for the entire duration of work (i.e., they are not free to move in between machine operations).

However, in setting up complex and heavy-duty machines, there's a need to be prudent in hiring highly skilled personnel who are cross-trained in machine setups, which comes at a great cost. This category of people is considered costly labor, which might not seem reasonable to hire and fire at will due to their scarcity and cost of hiring. Furthermore, these setup-operators are free to move in between setup operations (i.e., they can move after completing initial setups to subsequent ones) and are not required to stay for the entire duration of the work schedule. Hence, the need for the effective optimization of these limited resources should not be neglected. To this end, in this paper, we propose a new DRC-FJSSP problem that incorporates a limited number of cross-trained skilled setup-operators. For more information on the DRC systems, see other recent publications by [15], [11], [13], and the recent survey by [4]. The rest of this paper is organized as follows: Section 2 presents the problem to be addressed, its assumptions, and the corresponding notations. The proposed genetic algorithm (GA) and its components are presented in Section 3. Numerical examples are presented in Section 4 to illustrate the problem addressed in this paper and show the computational efficiency of the proposed algorithm. Finally, conclusions are given in Section 5.

2 Problem Statement, Assumptions and Notations

This section presents the problem to be addressed, its assumptions, and the corresponding notations. Generally, SRC-FJSSP consists of two major subproblems: sequencing of operations and the selection of machines. In contrast, DRC-FJSSP consists of the two major sub-problems of an SRC-FJSSP, with the addition of one more problem referred to as the selection of workers. Therefore, the DRC problem in this paper consists of three (3) subproblems, namely: (1) the selection of a machine for each operation, (2) the sequence of operations on selected machines, and (3) the selection of an eligible setup operator for setting up a machine. For this paper, the DRC-FJSSP in the presence of a scarce number of skilled cross-trained setup operators (SSO) will be hereafter denoted as "DRC-FJSSP-SSO."

2.1 Problem Statement

Consider a job-shop consisting of M-machines where certain machines m are similar or have some common functionalities. Also, the schedule of the system includes a set of J-independent jobs j with a number of operations O_j in a predefined arrangement where each operation o of job j can be processed on a set of alternative and eligible machines. The total time spent by an operation o of job j on machine m is defined as the setup-time denoted by $(S_{o,j,m})$ and the processing time (batch size B_j multiplied by unit processing time $T_{o,j,m}$). The setup of this operation o can be started once the assigned machine completes its previous operation, and an eligible setup operator is available. Furthermore, there are N setup-operators where each setup operator n (where $n = 1, \ \ldots, \ N$) is trained to perform setup of operation o on a given set of machines m. Hence, as seen in figure 1, the problem is the assignment of each operation to one of its alternative and qualified machines, determine the sequence and starting time of the operations on each machine and the eligible setup-operator for each machine. Figure 1 is a case of four jobs, three machines (i.e., partial flexibility), two setup-operators, and the setup-operators are trained to set up some of the machines (i.e., partial flexibility). For example, operation 1 of job 4 can be set up on both machine 2 and machine 3 by either setup-operator 1 or setup-operator 2, and operation 2 of job 4 can be setup on machine 1 by setup-operator 1 only, and on machine 3 by both setup-operator 1 and 2. Note that in a shop system, a machine is said to be partially flexible when all job-operations cannot be carried out on all the machine, and a setup-operator is also said to be partially flexible when he/she cannot carry out setup-operations on all machines (i.e., setup-operator 2).

2.2 Assumptions

The following assumptions were made for the model in addressing the problem in this paper:

(i) A machine can process at most a single operation at a given period of time (i.e., machine-capacity constraint)
(ii) Once the processing of an operation begins, it cannot be interrupted until it is done (i.e., Pre-emption not allowed).
(iii) Each operation of a job can be assigned to at most a single machine and a single eligible setup-operator at a given period of time (i.e., resource-constraint)
(iv) Modification is not allowed to the predetermined sequence of the operations for each job (i.e., precedence-constraint)
(v) Each setup-operation can be carried out by only one setup-operator (i.e., setup-operator constraint)
(vi) The nature of all setups are in detached mode (i.e., setup of a particular operation can begin before its arrival on the assigned machine)
(vii) The setup-operator's movement time is negligible.

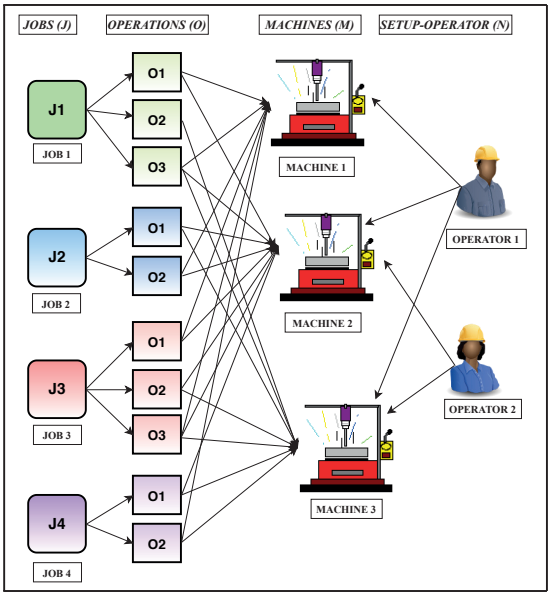

Fig. 1: A basic example of the DRC-FJSSP-SSO.

2.3 Necessary Notations

The following notations were used in the solution procedure in this paper. Additional notation and MILP formulation can be found in [10].

Indexes and Parameters:

m	An index for machines, where $m = 1, 2, 3, \ldots, M$, where M is the number of machine;
r	An index for machine run, where a run is defined as an processing of an operation by a machine;
n	An index of setup operator, where $n = 1, 2, 3, \ldots, N$, where N is the nubber of setup operators such that $N \ll M$.
k	An index of setup operation performed by an operator
$P_{o,j,m}$	A binary variable which takes the value 1 if operation o of job j can be executed on machine m, or 0 otherwise;
$\Theta_{n,m}$	A binary variable which takes the value 1 if setup operator n is eligible to perform setup on machine m, 0 otherwise
Ω	Large positive number.

Decision Variables:

$\widehat{C}_{r,m}$	Completion time of the rth run of machine m;
$s_{k,n}$	Completion time of the kth setup of setup-operator n; and
C_{max}	Completion time of all jobs ($Makespan$);

3 Components of the Proposed GA

3.1 Solution Representation

Solution representation in GA is a critical step in the algorithm's implementation. The solution representation technique used in this paper follows a similar concept used in [5]. However, as seen in figure 2(a), the triplet-gene solution encoding scheme used in [5] was improved into a new encoding scheme as seen in figure 2(b). Unlike the SRC-FJSSP where the machine is the only resource considered in the scheduling problem, an additional resource constraint is added to the SRC-FJSSP to make it DRC-FJSSP. Due to the addition of an extra constraint (i.e., setup-operators), the triplet(j, o, m) gene of a SRC-FJSSP is now augmented into a quadruple(j, o, m, n) gene for the DRC-FJSSP-SSO as shown in Figure 2(b), where the oth operation of job j that is assigned to the eligible machine m is setup by setup-operator n. Furthermore, for any given j, if o ¡ o', a gene with a value (j, o, m, n) must appears earlier in the sequence before the gene with value (j, o', m', n) irrespective of the values of m and m'. For a given gene value (j, o, m, n), the value of the indices should satisfy the condition set by eligibility indicator data, i.e., $P_{o,j,m} = 1$ and $\Theta_{n,m} = 1$.

3.2 Evaluation

Based on the assignment and sequencing information obtained from a solution string, the resulting starting and completion times of jobs and, hence the makespan of the schedule can be determined. The makespan is used to evaluate how fit the individual is. In calculating the makespan, we take into account the following: (1) the machine setup time by setup-operators, (2) the detached nature of setup, and (3) the cross-training ability of setup-operators. The procedure for this calculation is outlined below:

Step 1. Set $l = 1$

Step 2. For the particular solution-string under consideration, set the values of indices j, o, m and n as secured from gene at location l.

Step 3. Calculate the completion times $s_{k,n}$ and $\widehat{C}_{r,m}$

- If operation o of job j is the first operation assigned to run r of machine m and the first setup-operation k to be performed by setup-operator (n) on the same machine (i.e., $r = 1$, $o = 1$, $k = 1$) then:
  $s_{k,n} = S_{o,j,m}$ and $\widehat{C}_{r,m} = S_{o,j,m} + B_j \cdot T_{o,j,m}$
- If (a) operation $o > 1$ of job j is the operation assigned to run r of machine m and first setup-operation k to be performed by setup-operator (n) on the same machine (i.e., $r = 1$, $o > 1$, $k = 1$) and (b) operation $o - 1$ was assigned to run r' on machine m', then:
  $s_{k,n} = S_{o,j,m}$ and $\widehat{C}_{r,m} = \max\{S_{o,j,m};\quad \widehat{C}_{r',m'}\} + B_j \cdot T_{o,j,m}$.

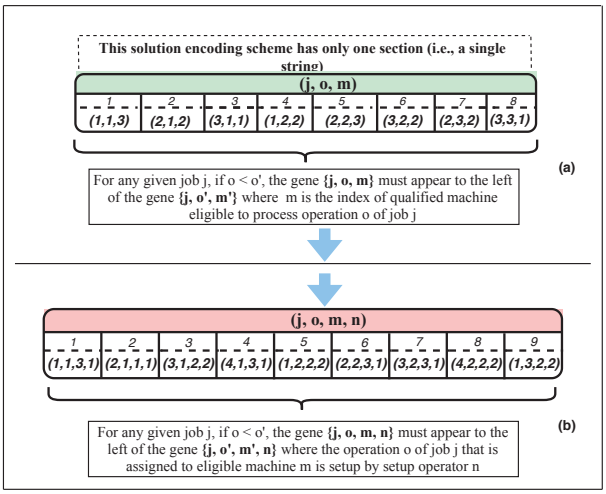

Fig. 2: Solution encoding schemes for (a) SRC-FJSSP and (b) DRC-FJSSP-SSO

- If operation o of job j is the operation to be processed on run $r > 1$ machine m and the setup-operation k is the first to be performed by setup-operator (n) machine m (i.e., $r > 1$, $o = 1$, $k = 1$) then:
  $s_{k,n} = \widehat{C}_{r-1,m} + S_{o,j,m}$ and $\widehat{C}_{r,m} = s_{k,n} + B_j \cdot T_{o,j,m}$
- If (a) operation $o > 1$ of job j is the operation to be processed on run $r > 1$ and the setup-operation k is the first to be performed by setup-operator (n) machine m (i.e., $r > 1$, $o > 1$, $k = 1$) and (b) operation $o - 1$ was assigned to run r' on machine m', then:
  $s_{k,n} = \widehat{C}_{r-1,m} + S_{o,j,m}$. and $\widehat{C}_{r,m} = \max\{s_{k,n}; \quad \widehat{C}_{r',m'}\} + B_j \times T_{o,j,m}$.
- If operation o of job j is the first operation assigned to run r on machine m and k is not the first setup to be performed by setup-operator (n) (i.e., $r = 1$, $o = 1$, $k > 1$) then:
  $s_{k,n} = s_{k-1,n} + S_{o,j,m}$. and $\widehat{C}_{r,m} = s_{k,n} + B_j \cdot T_{o,j,m}$
- If (a) operation o of job j is the first operation to be processed and k is not the first setup to be performed by setup-operator (n) on machine m (i.e., $r = 1$, $o = 1$, $k > 1$) and (b) operation $o - 1$ was assigned to run r' on machine m', then:
  $s_{k,n} = s_{k-1,n} + S_{o,j,m}$. and $\widehat{C}_{r,m} = \max\{s_{k,n}; \quad \widehat{C}_{r',m'}\} + B_j \times T_{o,j,m}$.
- If k is not the first setup to be performed by setup-operator (n) on machine m for operation $o = 1$ of job j (i.e., $k > 1$, $r > 1$, $o = 1$) then:
  $s_{k,n} = \max\{s_{k-1,n}; \quad \widehat{C}_{r-1,m}\} + S_{o,j,m}$ and
  $\widehat{C}_{r,m} = s_{k,n} + B_j \cdot T_{o,j,m}$
- If (a) k is not the first setup to be performed by setup-operator (n) on machine m for operation o of job j (i.e., $r = 1$, $o > 1$,

$k > 1$) and (b) operation $o-1$ was assigned to run r' on machine m', then:
$s_{k,n} = \max\{s_{k-1,n};\quad \widehat{C}_{r-1,m}\} + S_{o,j,m}$ and
$\widehat{C}_{r,m} = \max\{s_{k,n};\quad \widehat{C}_{r',m'}\} + B_j \times T_{o,j,m}$.

Step 4. If l is less than the total number of genes of the chromosome, increase its value by 1 and go to Step 2; otherwise go to Step 5

Step 5. Calculate the makespan of the schedule as $c_{max} = \max\ \widehat{C}_{r,m};\ \forall(r,m)\}$ and set the fitness of the solution to c_{max}.

3.3 Genetic Operators

GAs uses genetic operators to evolve a population of solutions towards a promising region of the search space. Generally, these operators are classified as selection, crossover, and mutation operators. The selection operator chooses the chromosomes for reproduction. In the proposed GA, a k-way tournament (KWT) and a roulette wheel selection (RWS) method was used to select individuals. The KWT selection method is used to first select k individuals randomly. Then, the individual with the highest fitness (smallest makespan) is declared the winner. This process of selection is repeated with replacement until the number of the new set of individuals is the same as the population size. In an RWS, the wheel is divided into sections according to the fitness of each solution-string and is rolled n-number of times where n is the same as the population size. In each spin, the solution-strings with the most extensive section on the wheel have a higher probability of been selected based on a higher fitness value. Once the individuals have been selected for reproduction, crossover and mutation operators are applied to the offspring. These operators can be classified as assignment and sequencing operators. The assignment operator only alters the assignment property of the parent chromosomes, while sequencing operators only alters the sequence of the operations in the parent chromosomes. The assignment operators used in this paper are (1) machine-operation assignment crossover, (2) machine-operation assignment mutation, (3) single-point crossover, and (4) setup-operator assignment mutation.

Assignment crossover operator is applied with probability α_1, and it produces offsprings by exchanging the assignment of arbitrarily chosen operations between two parents, as shown in figure 3. The assignment mutation operator is applied with probability α_2. It alters the assignment of a few operations of a given chromosome. In a single-point crossover, a point is arbitrarily selected on both parent 1 and parent 2, and labeled as the crossover point. The arbitrarily selected point is chosen with a probability of α_3, and all the genetic information beyond the selected point is exchanged between the parent-strings to produce new offsprings. Setup-operator mutation is applied with probability α_4 on the randomly selected solution-string. As seen in Figure 4, it alters the setup-operator assignment of the solution-string by assigning the setup-operator to an alternative machine that he/she is qualified to setup. The sequencing operators used in this paper are (1) job-operation sequence-order crossover and

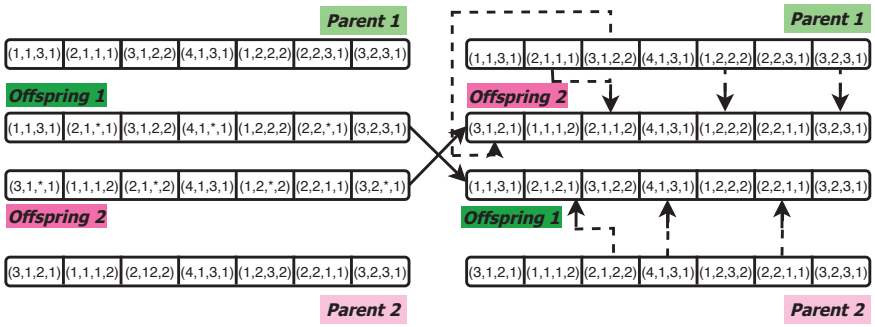

Fig. 3: Machine-operation assignment crossover.

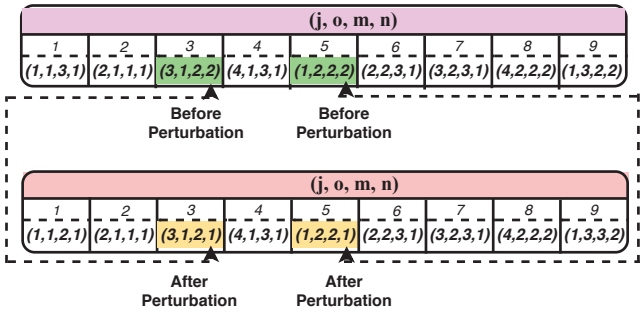

Fig. 4: Setup-operator assignment mutation.

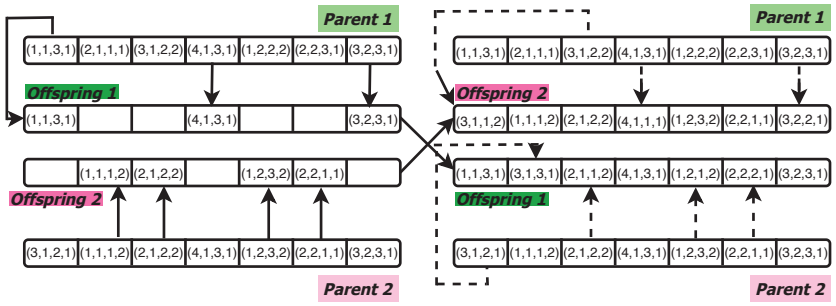

Fig. 5: Job-operation sequence-order crossover.

(2) operation sequence-swap mutation. With probability α_5, the job-operation sequence-order crossover operator is applied by randomly selecting one operation each from the parent chromosomes, copies all the operations of the job to which the selected operation belongs into the corresponding offsprings as illustrated in figure 5. It proceeds by completing the new offspring with the remaining operations in the same pattern of the second parent while maintaining the as-

signment structure of the operations in the first parent. This operator respects the precedence constraints among operations of the same job and ensuring it is not violated. The operation sequence-swap mutation operator is applied with a probability of α_6 on the solution-string in such a way that the position of the selected operation is swapped with another while ensuring that the precedence constraint is enforced.

4 Numerical Examples

In this section, we present an example problem to illustrate the features of the proposed model and the computational performance of the developed GA. A problem instance consisting of five machines, twelve jobs, and three setup-operators is considered. The batch size of each job is given in Table 1. This table contains, the number of operations in each job, the possible alternative machine routes for each operation, the eligible setup-operators for the machine, and the corresponding unit processing times and setup times. This example problem was solved using the Branch-and-Cut (BC) algorithm of ILOG CPLEX solver and the proposed GA for two different scenarios. In the first scenario, it is assumed that both the machines and the setup-operators are partially flexible. In contrast, in the second case, it is considered that only the setup-operators are flexible.

4.1 Solution Illustration

The developed GA was coded in C++ using Microsoft Visual Studio 2017. Both the ILOG CPLEX solver and the developed GA were implemented on a 64-bit operating system, 3.5 GHz Intel (R), 16GB RAM computer. The Gantt charts of the resulting schedules, as solved by the developed GA for the machines, is given in Figure 6, and the setup-operators is given in Figure 7. From Figure 8, it can be concluded that the developed GA ($makespan = 1605.0mins$) outperformed the Branch-and-Cut algorithm of the CPLEX solver ($makespan = 1927.5mins$) for both partial and total flexibility scenario ($GA - makespan = 1605.0mins, CPLEX - makespan = 2065.0mins$). In Figure 6, the detached nature of setup can be observed between operation 2 and 3 of job $j = 8$. It can be seen that the setup of operation 3 of job 8 can begin before the completion of operation 2 of job 8. The detached nature of setup also helps to reduce the idle or waiting time of setup-operators between consecutive machine setups as the setup-operator does not have to wait for the arrival of the previous operation of the job to begin setup for the next operation. For instance, setup-operator $n = 3$ would be able begin the setup of operation $o = 3$ of job $j = 8$ immediately after his last setup of operation $o = 2$ of job $j = 3$ at 367.5 due to the detached nature of setup, otherwise, the setup-operator would have to wait until operation $o = 2$ of job $j = 8$ is completed at 563.0 which would increase the potential idle-time by 35%. Furthermore, since there was no change in the makespan value for the two flexibility scenarios when solving with GA, it may be reasonable to say that for more work and cost-effectiveness, setup-operators can be trained on

some group of machines at a particular workstation than on all the machines in the entire shop system. This would also reduce the movement of setup-operators from one setup operation to another, resulting in a more cost effective and leaner manufacturing environment.

4.2 Algorithm Performance

Larger problem instances were developed to evaluate the performance of the genetic algorithm and the behavior of the algorithm to changes in genetic parameters. The case examples used in this study were generated and solved with different genetic problem-parameters for 10 test runs based on the provided procedures in [12] and in other GA published in the literature. Table 2 describes the general features of the case-examples, such as the problem instances, the total number of jobs, operations, machines, setup-operators, and alternative routes. The problem sizes used in this study are much larger than most of the ones used in literature. Figure 9 shows how the algorithm converges during iterations and how it responds to the tuning of genetic parameters for problems 3, 4, 5, and 6 after ten experimental runs. Problems 3 and 4 are considered as medium-sized problems, while problems 5 and 6 are regarded as large-size problems based on the total computational cost required during the iterations by the genetic algorithm. The genetic algorithm can converge during its iteration through a large generation in less computational time for medium-size problems while it takes more computational time to converge and progress from a certain number of generation to another in large-size problems.

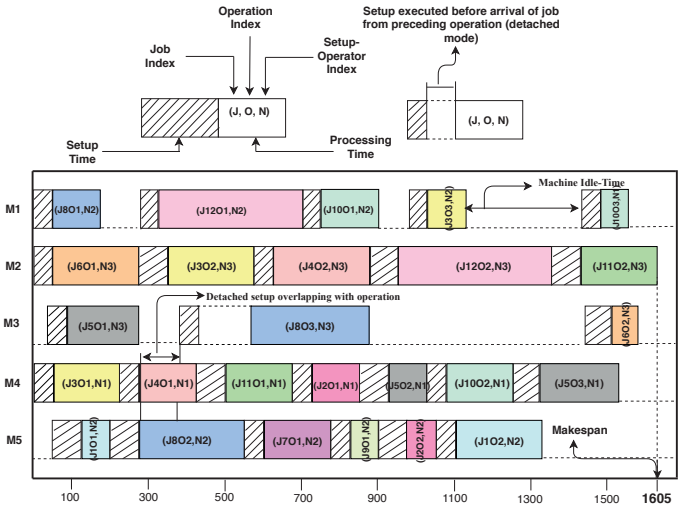

Fig. 6: Machines schedule for the example problem.

Table 1: Data for the twelve jobs, five machines, and three setup-operators

			Alternative routes, (m, n, $T_{o,j,m}$, $S_{o,j,m}$)		
j	B_j	o	1	2	3
1	50	1	(2, (2,3), 1.25, 40)	(5, 2, 1.5, 60)	
		2	(5, 2, 4.50, 60)		
2	35	1	(3, (2,3), 3.75, 40)	(4, 1, 3.50, 60)	
		2	(1, (1,2), 1.75, 40)	(4, 1, 1.75, 60)	(5, 2, 1.50, 80)
3	30	1	(2, (2,3), 6.75, 60)	(4, 1, 6.50, 40)	
		2	(2, (2,3), 7.00, 80)		
		3	(1, (1,2), 3.50, 40)	(2, (2,3), 3.25, 60)	(5, 2, 4.00, 40)
4	40	1	(2, (2,3), 4.00, 60)	(4, 1, 4.00, 40)	
		2	(1, (2,3), 2.50, 60)	(2, (2,3), 2.60, 80)	
5	30	1	(1, (1,2), 6.25, 40)	(3, (2,3) 6.75, 40)	(5, 2, 7.00, 40)
		2	(1, (1,2), 2.50, 60)	(3, (2,3), 2.75, 80)	(5, 2, 2.75, 80)
		3	(3, (2,3), 2.75, 80)	(4, 1, 3.00, 80)	(5, 2, 2.75, 40)
6	45	1	(2, (2,3), 5.50, 40)		
		2	(3, (2,3), 1.25, 60)		
7	45	1	(5, 2, 4.00, 40)		
8	55	1	(1, (1,2), 2.00, 60)	(4, 1, 1.25, 60)	
		2	(1, (1,2), 5.75, 40)	(5, 2, 5.25, 80)	
		3	(3, (2,3), 6.00, 60)	(5, 2, 6.00, 80)	
9	30	1	(1, (1,2), 3.00, 60)	(3, (2,3), 2.75, 80)	(5, 2, 2.75, 40)
10	40	1	(1, (1,2), 4.00, 40)		
		2	(1, (1,2), 6.75, 60)	(4, 1, 7.00, 40)	
		3	(1, (1,2), 1.25, 60)		
11	50	1	(1, (1,2), 3.25, 40)	(2, (2,3), 4.00, 80)	(4, 1, 3.25, 80)
		2	(2, (2,3), 3.25, 80)		
12	55	1	(1, (1,2), 7.00, 40)		
		2	(2, (2,3), 7.00, 80)		

Table 2: Data for larger problem instances.

	Total Number of				
			operations for		alternative routes
Problem No.	Machines	Jobs	the Jobs	Setup-Operators	for the operation
3	9	15	34	4	97
4	13	20	81	6	190
5	10	35	154	4	462
6	15	50	243	7	495

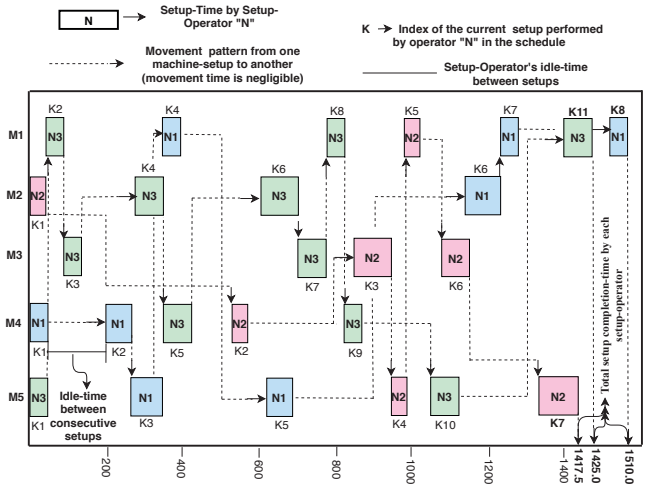

Fig. 7: Setup-operators schedule for the example problem.

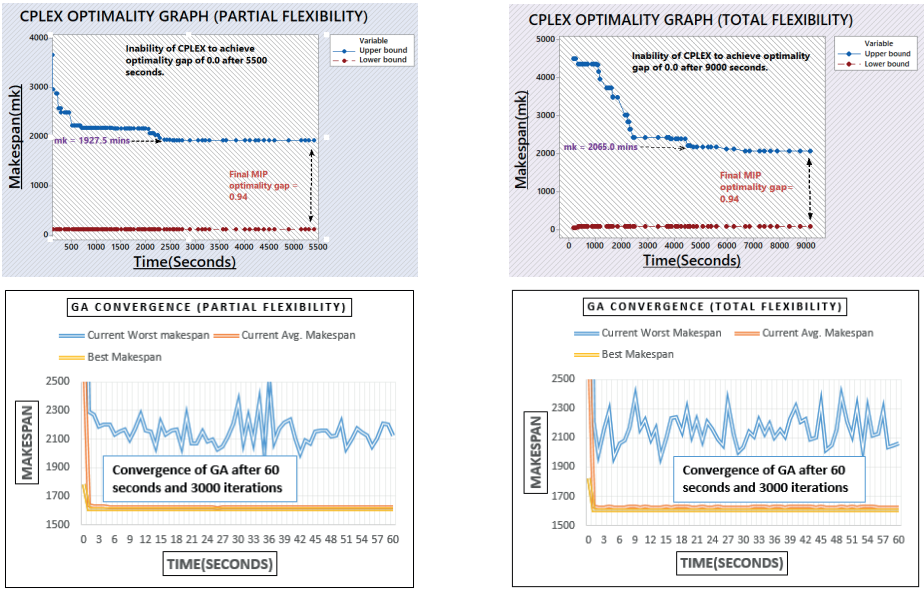

Fig. 8: Convergence behaviour of the GA and CPLEX solver.

5 Conclusions and Future Research

In this paper, we considered a DRC system that incorporates an additional resource of scarce cross-trained setup-operators with the detached nature of machine setups. The BC algorithm of the ILOG CPLEX solver and the proposed

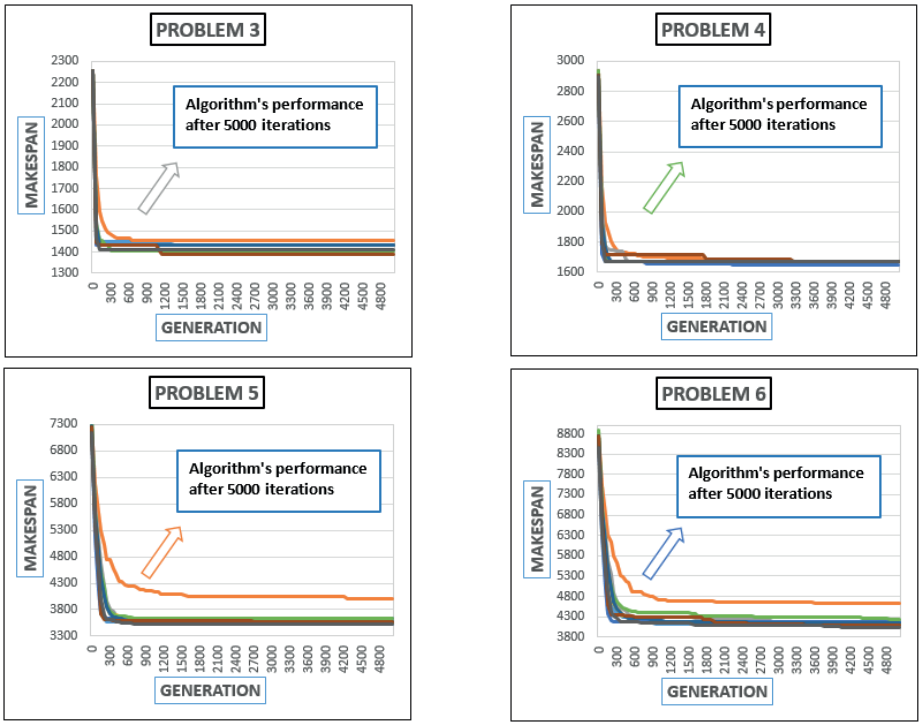

Fig. 9: Convergence behaviour of the GA for larger problem set over 10 runs.

GA was used in addressing an example problem. The results showed that the developed GA outperformed the BC algorithm both in the quality of solutions and the required computational cost. The performance from the GA further amplifies the dominance of metaheuristics approach to solving complex problems with less computing cost, and it also provides a good and promising foundation for further studies in limited cross-trained human-resource DRC systems. In our future research, we plan to extend the model and the solution procedure to consider multiple objectives such as machine workload-balancing, due dates, and other factors such as machine release dates, sequence-dependency setup times, and transportation time of setup-operators between setups.

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Using the k-chaining approach to solve a stochastic days-off-scheduling problem in a retail store

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Abstract. The present study addresses the personnel assignment and scheduling problems through the multiskilling flexibility strategy with the aim of reducing the negative impacts on a company's cost structure that come as a result of demand uncertainty. The personnel assignment matter is handled using the chaining approach and it is evaluated whether a multiskilled workforce that minimizes the expected costs associated with training and under/overstaffing can be planned while taking into account demand uncertainty and using the k-chaining policy for a days-off scheduling problem. Until now, literature's main focus has been 2-chaining policies, where every multiskilled employee is at most trained in two departments, i.e., k =2. Hence, this research intents to determine scenarios where a k-chaining policy with k≥2 offers more cost-effective multiskilling structures than a 2-chaining one. Initially, a deterministic mixed-integer linear optimization model is developed and then modified into a two-stage stochastic optimization model in order to add demand uncertainty. Such methodology is subsequently applied to a Chilean retail store where a Monte Carlo simulation is used to generate different daily demand scenarios. The results obtained suggest that with high levels of demand variability k-chaining policies seem favorable. Nonetheless, none of the employees evaluated were able to work in more than three departments, which leads to the conclusion that it does not appear to be advantageous to implement excessive flexibility levels.

Keywords: Personnel scheduling, Multiskilling, Chaining, Labor flexibility, Retail.

1 Introduction

An adequate personnel scheduling strategy is not only essential to a company in terms of securing a competitive advantage and thus acquiring means to outperform its competitors within a continuously growing market, but also in regard to the decrease of workforce related costs that both manufacturing and service companies must discharge.

Demand seasonality is a predictable phenomenon typically faced by the service sector that affects a company's usual personnel scheduling system since special needs must be met. Formulating such system becomes a challenging activity for the retail trade especially when unpredictable phenomena such as demand uncertainty and staff absenteeism are taken into account, for the mismatch between demand and supply ought to be reduced as much as possible [1 , 2 , 3]. As a result of the service industries' inherent variability, firms eventually face situations where the number of employees is below staff requirements (understaffing) or where there are more employees than the actual amount needed (overstaffing).

Therefore, in order to protect themselves from uncertainty and hence reduce the mismatch between employee supply and demand, enterprises apply several flexibility strategies such as a multiskilled staff [4 , 5 , 6 , 7]. By implementing this strategy in the retail industry, the operational manager of a retail store is able to transfer multiskilled employees from overstaffed departments to those understaffed. However, since training employees is costly, it is necessary to identify efficient multiskilling designs in order to obtain a maximum of benefits from this approach at a reasonable cost.

Assigning multiskilled staff to different activities can be modeled as an assignment problem in a bipartite graph where the supply nodes are employees, and the demand nodes are the departments of a store. These types of designs are known as chained multiskilling designs where different multiskilling structures can be arranged. Amongst the most evaluated structures by previous works in the literature we can find closed long chains (CLC) and closed short chains (CSC). A CLC is a bipartite graph where there is a multiskilled employee in each department so that its arcs form exactly one undirected cycle, while a CSC is an induced bipartite subgraph that forms an undirected cycle since there is a subset of multiskilled employees that only connects a subset of departments.

Particularly, the 2-chaining policy, where certain employees are trained in two departments, i.e., k =2, has been acknowledged by many studies as the most popular and endorsed chaining policy [4 , 6 , 8 , 9 , 10 , 11]. However, it would be interesting to analyze scenarios where a certain number of employees are able to work in k departments with k≥2. This type of policy is known as k-chaining and only a few studies have evaluated its benefits before. Figure 1 shows a comparison between a 2-chaining structure with one CLC and one CSC, and a k-chaining structure with k=3.

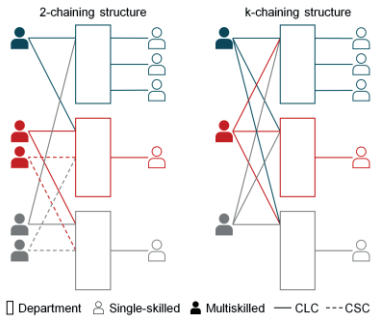

Fig. 1. Comparison between a 2-chaining structure with one CLC and one CSC, and a k-chaining structure with k=3.

Therefore, the present study evaluates if it is possible to plan a multiskilled staff, using the k-chaining approach and considering demand uncertainty, that minimizes the expected costs associated with training and under /overstaffing for a days-off scheduling problem. A deterministic mixed-integer Linear Programming (MILP) model is initially proposed as a foundation for the stochastic analysis. Subsequently, a Two Stage Stochastic Optimization (TSSO) MILP model is developed and thus applied to a case study of a Chilean retail store.

2 Literature review

Previous studies have analyzed the multiskilling as a useful strategy to address scheduling personnel problems with the aim of minimizing the gap between demand and supply. A series of these articles is presented in Table 1. The following symbology is introduced to contextualize the main aspects in consideration:

1. *Decision level of Human Resources studied (ND-RH):* The ND-RH column indicates which decision problems were covered in each study. At the planning level, the main decision problem would be to determine the staffing by type of task and contract (S). At the scheduling level, the decision problems are: (i) shift scheduling (SS), that is, assigning employees to daily shifts; (ii) day off scheduling (DOS), that is, assigning employees to days off between their working days over a given planning horizon; and (iii) Tour scheduling (TS), that is, the simultaneous assignment of days off and shifts. Finally, the assignment level (A) simply consists of assigning employees to particular types of tasks regardless of their corresponding shifts.
2. *Chaining (CH):* Indicates if any sort of chaining application is present in the model, if there is not (-), if there is chaining in maximum two types of tasks (2-chaining), if there is chaining in three or more tasks types (k-chaining with k>2).
3. *Multiskilling (MS):* Indicates whether the study uses a parameter (Par) representing an employee's fixed skills or a variable (Var) representing the decision as to whether or not an employee is trained in a given additional task type.
4. *Constraint of maximum number of skills in the model (MSP):* Indicates the maximum number of skills per employee that the model allows for the solution.
5. *Number of skills in the solution (NSS):* Indicates the resultant value of the number of skills per employee present in the solution.
6. *System type (ST):* (i) homogeneous (Hom), meaning that all task types, departments or resources in the system are identical, each one having the same supply level and installed capacity as well as possessing an identical demand and level of productivity, multiskilling and probability of absenteeism; (ii) heterogeneous (Het), meaning that not all the task types or departments are identical.
7. *Demand uncertainty (DU):* Indicates whether or not the problem considers variability in the staff demand.
8. *Supply uncertainty (SU):* Indicates whether or not the problem considers variability of supply or staff absenteeism.

9. *Method:* Indicates the solution method used, may be: (i) heuristics (H); (ii) simulation (S); (iii) optimization (OPT); (iv) Markov processes (MP); (v) analytic (AN); (vi) queuing theory (QT); (vii) algorithm (AL); (viii) genetic algorithm (GA); (ix) constraint-based selection procedure (CODEMI); (x) constraint scheduling (CS) and (xi) statistical analysis (SA).
10. *Application (AP):* The industry or sector where the proposed model was applied in the study, which may be (i) manufacturing (M); (ii) services (S); (iii) call centers (CC); (iv) health (H); (v) retail (R); (vi) Power plant (CE); (vii) Cyber Security Operations Center (CS); (viii) Construction (C).

Table 1. Characteristics of published studies related to chaining and multiskilling.

Reference	ND-RH	CH	MS	MSP	NSS	ST	DU	SU	Method	AP
Brusco and Johns [12]	S+SS	k-cha	Par	≤3	≤3	Het	No	No	OPT	S
Cai and Li [13]	SS+ DOS+A	-	Par	≤2	≤2	Het	No	No	GA, H	S
Gomar et al. [14]	A	-	Par	-	≤3	Het	No	No	S	C
Eitzen et al. [15]	DOS+ SS	-	Par	≤9	≤3	Het	No	No	AN	CE
Inman et al. [16]	S+A	2-cha	Par	≤2	≤2	Hom	No	Yes	S	M
Iravani et al. [17]	A	k-cha	Par	≤6	≤2	Het	Yes	Yes	S	CC
Yang [18]	A	k-cha	Par	-	≤2	Het	No	Yes	S	M
Simchi-Levi and Wei [8]	A	2-cha	Par	≤2	≤2	Het	Yes	No	AN	M
Deng and Shen [19]	A	2-cha	Par	≤2	≤2	Het	Yes	No	OPT, S, AN	M
Paul and MacDonald [20]	S + A	2-cha	Var	≤2	≤2	Het	Yes	No	H, OPT, AN	H
Olivella and Nembhard [21]	A	-	Var	-	≤3	Hom	Yes	Yes	CODEMI	M
Henao et al. [9]	A	2-cha	Var	≤2	≤2	Het	Yes	No	OPT, H, S	R
Ahmadian Fard Fini et al. [22]	S+A	-	Var	≤3	≤3	Het	No	No	CS, GA	C
Ağralı et al. [23]	SS	-	Par	≤10	≤10	Het	No	No	OPT	S
Liu [24]	D+A	2-cha	Par	≤2	≤2	Het	Yes	No	OPT, S	M
Taskiran and Zhang [25]	S+TS	-	Var	≤4	≤4	Het	No	No	OPT	CC
Henao et al. [10]	A	2-cha	Var	≤2	≤2	Hom	Yes	No	AN+S	R
Porto et al. [4]	TS+S	2-cha	Var	≤2	≤2	Hom	No	No	OPT	R
Altner et al. [26]	DOS	-	Var	-	≤6	Hom	Yes	No	OPT, H	CS

According to Table 1, in the vast majority of the studies the multiskilling effect it is entered as a fixed data input, which restricts the possibilities of obtaining better solutions This issue could be solved by using a decision variable instead.

Subsequently, it can be noticed that it is frequently concluded that by training the personnel in a maximum of one additional skill, optimal results are obtained in terms of budget and level of service. However, it is not common to execute chaining methods in the solution procedures, which are considered of utmost importance to evaluate the impact that its application may possibly cause in this type of systems in relation to a more accurate approach to the optimal number of additional skills required per employee.

In addition, we identify that in the scarcely articles where chaining is contemplated, the 2-chaining method is usually applied (k = 2), only few studies implement multi-skilling as an unrestricted decision variable for the purpose of developing k-chaining setups. It is also evident that a large section of articles does not evaluate demand uncertainty.

In summary, this study aims to fill the gaps identified from the literature review by solving a days-off-scheduling problem that minimizes the under/overstaffing costs, using a multiskilled staff with a k-chaining approach, and taking into account the demand uncertainty.

3 Problem description

The problem under study consists in planning a multiskilled workforce, over a two-week horizon, that helps mitigate the negative impacts of the inherent uncertainties involved in the personnel scheduling process. Specifically, the problem we propose addresses the retail industry and seeks to minimize the costs associated with training and personnel shortage/surplus. In addition, this research aims to define robust multiskilling structures through k-chaining policies with $k \geq 2$, involving CLCs and/or CSCs, for a days-off scheduling human resources decision level. Since training employees is costly, the solution of this problem will define the most cost-effective multiskilling structure that not only minimizes the training cost but also guarantees robusticity against different levels of demand variability.

Briefly, the solution of this problem will determine: (i) how many employees should be single-skilled and how many should be multiskilled; (ii) the amount of additional skills each multiskilled employee should have; and (iii) under what levels of demand uncertainty a 2-chaining policy or a k-chaining policy with $k \geq 2$ is required. The solution will also assign rest days between working days to each employee over the two-week planning horizon.

In order to obtain those results, we formulate deterministic (see section 4.1) and stochastic (see section 4.2) models that consider the following assumptions: (i) Training costs are included in the total cost function and assumed to be the same for each department. (ii) The staff shortage/surplus cost per person-hour is assumed to be the same for each department and independent of the size of the staff shortage/surplus. (iii) The hours available for assignment in any department at the start of the planning horizon are exactly equal to the value in hours of that department's mean demand. (iv) There is no uncertainty of supply, that is, no staff absenteeism. (v) All employees have the same contract and therefore work the same number of weekly hours. (vi) Each employee should get at least one weekend off during the two-week planning period. (vii) At the start of the planning horizon, all employees are single-skilled and, thus, they can work only in a single department. (viii) Employees are homogeneous, i.e. all equally productive.

4 Methodology

The objective of the present section is to structure a workforce using the k-chaining approach for a days-off scheduling problem while considering uncertain demand. In Subsection 4.1, a deterministic optimization model is proposed for solving the addressed problem. Then, in Subsection 4.2, we present a two-stage stochastic optimization model for determining the robust multiskilling levels that minimize the expected under/overstaffing and training costs.

4.1 Deterministic optimization model

In this subsection we present a deterministic version of the mixed-integer linear programming model useful to solve the personnel days-off scheduling problem with k-chaining. Later, in Subsection 4.2, we will introduce the necessary modifications to incorporate demand uncertainty. First, let us define the model's sets, parameters and variables and their respective notation.

Model sets:

I : Store employees, indexed by i.

L : Store departments, indexed by l.

I_l : Store employees under contract in department l , $I_l \subseteq I, \forall\ l \in L$

S : Weeks, indexed by s. {1, 2}.

D : Days of the two-week period, indexed by d {1, 2, ..., 13,14}

D_S : The set of days during week s of the two-week period.

$D5_d$: Next five consecutive days in the two-week period after day d . For example, $D5_2$ = {3, 4, 5, 6, 7}, where day 2 corresponds to the first week's Tuesday and day 7 corresponds to the first week's Sunday.

D^+ : Maximum consecutive days, indexed by d {1, 2, ..., 8, 9}.

Model parameters:

c : Cost of training an employee to work in any department; [$-biweek/employee].

u : Staff shortage cost per hour (equivalent to the expected cost of lost sales); [$/Hour].

o : Staff surplus cost per hour (equivalent to the opportunity cost of idle employee-hours); [$/Hour].

r_{ld} : Number of hours required in department l on day d , $\forall l \in L$, $d \in D$.

t : Number of daily hours employees must work under store employment contract.

m_i : Department for which employee i was initially trained, $\forall\ i \in I$.

Model decision variables:

x_{il}: Equal to 1 if employee i is trained for department l, otherwise 0, $\forall i \in I$, $l \in L$.

y_{id}: Equal to 1 if employee i works on day d, otherwise 0, $\forall i \in I$, $d \in D$.

ω_{ild}: Number of working hours assigned to employee i on day d in department l, $\forall i \in I$, $l \in L$, $d \in D$.

z_i: Equal to 1 if employee i does not work on the first weekend (day 6, day 7) and 0 if employee i does not work on the second weekend (day 13, day 14) $\forall i \in I$.

v_i: Number of additional skills for employee i, $\forall i \in I$.

k_{ld}: Staff shortage in daily hours in department l on day d, $\forall l \in L, d \in D$.

δ_{ld}: Staff surplus in daily hours in department l on day d, $\forall l \in L, d \in D$.

The deterministic mixed-integer linear programming (MILP) model can now be formulated as follows:

$$Min \underbrace{\sum_{i \in I} \sum_{l \in L: l \neq m_i} c x_{il}}_{(a)} + \underbrace{\sum_{d \in D} \sum_{l \in L} (u k_{ld} + o \delta_{ld})}_{(b)} \tag{1}$$

s.t.

$$\sum_{i \in I} \omega_{ild} + \kappa_{ld} - \delta_{ld} = r_{ld} \qquad \forall l \in L, d \in D \tag{2}$$

$$\omega_{ild} \leq t x_{il} \qquad \forall i \in I, l \in L, d \in D \tag{3}$$

$$\sum_{l \in L} \omega_{ild} = t y_{id} \qquad \forall i \in I, d \in D \tag{4}$$

$$\sum_{d \in D_S} y_{id} = 5 \qquad \forall i \in I, s \in S \tag{5}$$

$$y_{id} + \sum_{\bar{d} \in D5_d} y_{i\bar{d}} \leq 5 \qquad \forall i \in I, d \in D^+ \tag{6}$$

$$y_{id} \leq 1 - z_i \qquad \forall i \in I, d \in \{6,7\} \tag{7}$$

$$y_{id} \leq z_i \qquad \forall i \in I, d \in \{13,14\} \tag{8}$$

$$x_{il} = 1 \qquad \forall i \in I, l \in L : l = m_i \tag{9}$$

$$v_i = \sum_{l \in L: l \neq m_i} x_{il} \qquad \forall i \in I \tag{10}$$

$$\sum_{i \in I_l} v_i = \sum_{i \in [I - I_l]} x_{il} \qquad I_l \subseteq I, \quad \forall l \in L \tag{11}$$

$$z_i \in \{0,1\} \qquad \forall i \in I \tag{12}$$

$$x_{il} \in \{0,1\} \qquad \forall i \in I, l \in L \tag{13}$$

$$y_{id} \in \{0,1\} \qquad \forall i \in I, d \in D \tag{14}$$

$$v_i \geq 0 \qquad \forall i \in I \qquad (15)$$

$$k_{ld} \geq 0 \qquad \forall l \in L, d \in D \qquad (16)$$

$$\delta_{ld} \geq 0 \qquad \forall l \in L, d \in D \qquad (17)$$

$$\omega_{ild} \geq 0 \qquad \forall i \in I, l \in L, d \in D \qquad (18)$$

In this formulation the objective function (1) minimizes the following costs: (a) training of employees in additional skills; and (b) staff shortage/surplus. Constraints (2), (16) and (17) yield the level of (non-negative) staff shortage/surplus associated with each department. Constraint (3) ensures the employees work the number of hours required by the employment contract only in departments they have been trained for. Constraint (4) guarantees the employees work the number of daily hours required by the employment contract only on the days they have been scheduled to work. Constraints from (5) to (8) implement days off scheduling constraints developed by Altner et al. [26]. Constraint (5) ensures each employee works exactly five days per week. Constraint (6) guarantees each employee works at most five consecutive days. Constraints (7) and (8) ensure each employee gets at least one weekend off. Constraints from (9) to (11) implement k-chaining constraints. Constraint (9) determines the department each employee was originally trained for. Constraint (10) indicates the number of additional departments an employee is trained for. Constraint (11) guarantees that for each department *l*, the number of employees belonging to it that have also been trained to work in other departments, is equal to the number of employees belonging to other departments that have been reciprocally trained to work in department *l*. Constraint (11) also ensures the formation of long or short closed chains. Either case requires that the indegree of each supply node belonging to the chain is equal to the outdegree of its corresponding demand node. Finally, constraints (12)-(18) define the domain of each problem variable.

4.2 Two stage stochastic optimization model

As mentioned before, in this subsection it is intended to describe the modifications applied to the original deterministic model in order to incorporate demand uncertainty in the stochastic model.

The approach that will be used to incorporate the uncertainty assumes that uncertainty is present in certain parameters of the problem, being denoted by ε. Along with this fact, it also assumes that the probability distribution of these uncertain parameters is perfectly known and deducted from historical data. The two-stage stochastic optimization (TSSO) approach begins by dividing into two sets the decision variables: first-stage and second-stage. The first-stage variables are represented by the vector *x*, and are decisions known as "here-and-now" because they are made before the actual perception of the uncertain parameters becomes available. The second- stage variables, *y(x)*, known as "wait and see" are taken after the realization of uncertainty and in consequence they can be denoted as $y(x, \varepsilon)$.

In addition, the TSSO problems are commonly solved by the sample average approximation (SAA) approach that creates one set of second-stage variables for every possible scenario. The quality of the SAA approach is high when it is generated a large enough, although finite, set of samples from the continuous distribution of the random parameters ε, represented by $\varepsilon \in \otimes$, where $\otimes$ is the set of scenarios generated. The first-stage variables x_{il}, v_i are related to decisions about train employees in a different department. These tactical decisions are made before the random realizations of the weekly demand are known. The second-stage variables, $\omega_{ild}(\varepsilon), k_{ld}(\varepsilon), \delta_{ld}(\varepsilon)$ are the operational adjustments once the uncertain demand in each department, $r_{ld}(\varepsilon)$ is observed. That is, after demands become known, staff shortages or surpluses may occur.

Taking this under appreciation, the two-stage stochastic MILP model can now be formulated as follows:

$$Min \quad \underbrace{\sum_{i\in I}\sum_{l\in L: l\neq m_i} cx_{il}}_{(first-stage)} + \underbrace{\frac{1}{|\otimes|}\left[\sum_{d\in D}\sum_{l\in L}\sum_{\varepsilon\in\otimes} (uk_{ld}(\varepsilon) + o\delta_{ld}(\varepsilon))\right]}_{(second-stage)} \tag{19}$$

s.t.

$$\sum_{i\in I}\omega_{ild}(\varepsilon) + \kappa_{ld}(\varepsilon) - \delta_{ld}(\varepsilon) = r_{ld}(\varepsilon) \qquad \forall l\in L, d\in D, \varepsilon\in\otimes \tag{20}$$

$$\omega_{ild}(\varepsilon) \le tx_{il} \qquad \forall i\in I, l\in L, \varepsilon\in\otimes \tag{21}$$

$$\sum_{l\in L}\omega_{ild}(\varepsilon) = ty_{id} \qquad \forall i\in I, d\in D, \varepsilon\in\otimes \tag{22}$$

$$\sum_{d\in D_S} y_{id} = 5 \qquad \forall i\in I, s\in S \tag{23}$$

$$y_{id} + \sum_{\bar{d}\in D5_d} y_{i\bar{d}} \le 5 \qquad \forall i\in I, d\in D^+ \tag{24}$$

$$y_{id} \le 1 - z_i \qquad \forall i\in I, d\in\{6,7\} \tag{25}$$

$$y_{id} \le z_i \qquad \forall i\in I, d\in\{13,14\} \tag{26}$$

$$x_{il} = 1 \qquad \forall i\in I, l\in L: l = m_i \tag{27}$$

$$v_i = \sum_{l\in L: l\neq m_i} x_{il} \qquad \forall i\in I \tag{28}$$

$$\sum_{i\in I_l} v_i = \sum_{i\in[I-I_l]} x_{il} \qquad \forall l\in L \tag{29}$$

$$z_i \in \{0,1\} \qquad \forall i\in I \tag{30}$$

$$x_{il} \in \{0,1\} \qquad \forall i\in I, l\in L \tag{31}$$

$$y_{id} \in \{0,1\} \qquad \forall i\in I, d\in D \tag{32}$$

$$v_i \ge 0 \qquad \forall i\in I \tag{33}$$

$$k_{ld}(\varepsilon) \ge 0 \qquad \forall l\in L, d\in D, \varepsilon\in\otimes \tag{34}$$

$$\delta_{ld}(\varepsilon) \geq 0 \qquad \forall l \in L, d \in D, \varepsilon \in \otimes \tag{35}$$

$$\omega_{ild}(\varepsilon) \geq 0 \qquad \forall i \in I, l \in L, d \in D, \varepsilon \in \otimes \tag{36}$$

In this formulation the objective function (19) minimizes the following costs: First-stage, training of employees in additional skills; and Second-stage, expected staff shortage/surplus. In summary, the constraints (2)-(4) and (16)-(18) were modified to explicitly incorporate uncertainty. Note that all these constraints involve only second-stage variables. Thus, the constraints (5)-(15) did not receive any modification because they are associated with first-stage variables. In addition, note that the interpretation of the constraints (20)-(36) and the constraints (2)-(18) is the same.

5 Computational experiments

The developed methodology was applied to a case study of a Chilean retail store. Regarding the deterministic model (1)-(18), it was written in AMPL and solved using the software CPLEX running through a computer with a random-access memory of 4 gigabytes. Regarding the TSSO model (19)-(36), it was also written in AMPL and solved using the software CPLEX running through NEOS-server, a free internet-based service for solving numerical optimization problems, subjected to a computational restricted time limit of 8 hours. The following subsections will elaborately describe the case study considered and the results obtained from the approach used.

5.1 Case study

We use real and simulated datasets to solve the proposed methodology. As to the real dataset, information concerning the size of the departments, initial skills of each employee and type of contract assigned to each employee, was retrieved from the Chilean retail store considered in this study. A total of 30 employees were analyzed within a 6 department store, that is, $|I| = 30$ and $|L| = 6$. A 9-hour full-time contract was assumed for the whole workforce; hence all employees should work exactly 5 days per week, resulting in 45 hours per week.

As for the costs parameters, the one related to staff shortages is equal to $u = US\$\ 60/h$ while staff surpluses represent a cost of $o = US\$\ 15/h$ [27]. The training cost per employee is assumed minimal, that is, $c = US\$\ 1\text{-}biweek/employee$. Since training employees is almost free of charge, the results obtained from this research could be evaluated as an upper bound on the potential beneficence of multiskilling [1 , 9 , 10].

In this study we considered the correspondent in-sample data, which alludes to the initial information used to attain the Multiskilled Personnel Days-off Scheduling Problem solution with uncertain demand. We used the TSSO approach, which is solved using a SAA method. To obtain this in sample-data we appeal to a classic Monte Carlo simulation to generate 60 scenarios at random which in the same way represent the possible future parameters of the daily demand $r_{ld}(\varepsilon) \quad \forall l \in L, d \in D, \varepsilon \in \otimes$, such that $|\otimes| = 60$.

This exact procedure is repeated as many times as possible to produce proper random demand values for each department under three coefficients of variation (CV) of the demand, which were 10%, 30% and 50%. Followed by these values, we assign a zero-truncated normal distribution to the stochastic demand in each department to avoid negative demand values which are not possible events.

For the purpose of studying the multiskilling levels defined using the k-chaining approach, the following metrics were evaluated.

First, the percentage of multiskilled employees: number of multiskilled employees required in relation to the total number of hired employees.

$$\%ME = \frac{\sum_{l \in L} \lambda_l}{|I|}.100 \tag{37}$$

Second, the percentage of multiskilled employees with h additional skills: number of multiskilled employees with h additional skills in relation to the total number of hired employees. Being m_{lh} the number of multiskilled employees belonging to department l with h additional skills,

$$\%ME_h = \frac{\sum_{l \in L} m_{lh}}{|I|}.100 \qquad \forall h \in \{1,2,3,4,5\} \tag{38}$$

Third, the percentage of total multiskilling: Number of additional skills that have been trained, relative to the theoretical maximum, in this case 150.

$$\%TM = \frac{\sum_{i \in I} \sum_{l \in L: l \neq m_i} x_{il}}{|I|(|L|-1)}.100 \tag{39}$$

5.2 Results and discussion

In order to analyze the results obtained from applying the methodology developed to a Chilean retail store, various aspects regarding both the deterministic and stochastic models will be presented. As expected, the computational time was way higher for the TSSO zero-truncated (TSSO-ZT) problem than for the deterministic one (DT). Apropos of the size of each model, the following table exhibits some important measures.

Table 2. Size of the deterministic and stochastic models

Model	Constraints	Binary variables	Continuous variables
TSSO-ZT	156 738	600	161 322
DT	3 102	600	2 730

Multiskilling decisions. Table 3 presents the results obtained once each of the metrics presented in the case study section was evaluated. Figure 2 shows the number of employees trained in one additional skill (k=2) and two additional skills (k=3) for each CV.

Table 3. Metrics used to measure the multiskilling requirements.

%CV	%ME	$\%ME_1$	$\%ME_2$	%TM
10	47	40	7	11
30	83	80	3	17
50	100	77	23	25

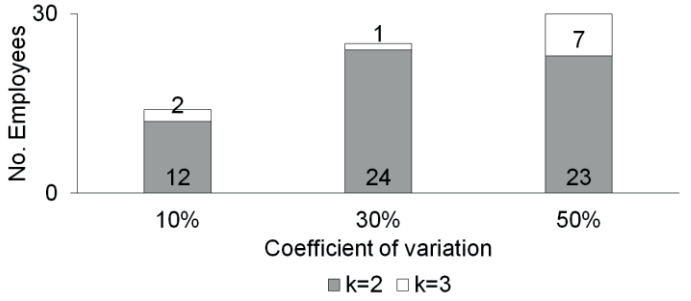

Fig. 2. Number of multiskilled employees trained in one additional skill (k=2) and two additional skills (k=3).

For a stochastic problem where 60 demand scenarios were generated, the ME, ME_1 and TM increase as the coefficient of variation rises. As to the ME_2, its greatest and lowest percentage are achieved at the CV = 50% and 30% respectively, behavior that could be explained by the quantity of demand scenarios analyzed.

It is also observed that when the demand variability is the highest (i.e., CV=50%) the ME reaches its theoretical maximum. Since the problem does not constraint the amount of additional skills an employee can acquire, it is expected that the resulting levels of multiskilling for the CV= 50% are those that not only most likely minimize the under/overstaffing cost, but also work as an upper bound on the potential beneficence of multiskilling considering the low training cost employed. The maximum amount of additional skills obtained was two, that is, there are some employees who are able to work in three different departments.

As to the highest level of demand variability, every single employee is multiskilled, just as assured before with the ME metric. In this scenario, 7 out of 30 employees were trained in two additional skills and the remaining 23 were trained in one additional skill.

Although the maximum number of employees trained in more than one additional skill is obtained at the CV= 50%, at both CV= 10% and 30% some employees are able to work in more than 2 departments. These results demonstrate that k-chaining policies with $k \geq 2$ are convenient, especially when the demand variability levels are high. It could also be concluded that flexibility structures with $k>3$ are not quite attractive since such amount of multiskilling could be impractical. However, a larger amount of demand scenarios should be evaluated in order to make a more objective statement.

Days-off-scheduling decisions. Figure 3 shows the number of employees assigned in each day of the second week of the planning horizon, indicating if the employee is single-skilled, trained in one additional skill (k=2) or trained in two additional skills (k=3), considering the demand variability with CV = 10%, 30% and 50%. It is observed that when the demand variability is low (CV = 10% and 30%) there are more employees assigned to work on the weekends (Saturday and Sunday), but as the demand variability increases (CV = 50%) the number of employees assigned to work on the weekends is less or equal to any other day of the week. Also, when the demand variability is the lowest (CV = 10%) there are more single-skilled employees, but these decrease in inverse proportion with the CV, and when the demand variability is the highest (CV = 50%) all employees are multiskilled.

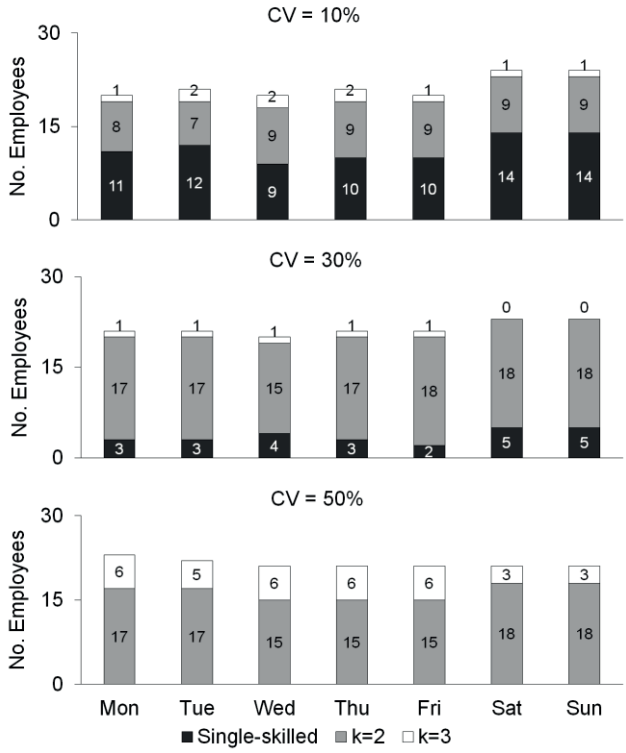

Fig. 3. Number of employees assigned in each day of the second week of the planning horizon.

6 Conclusions

Through the development of this study we were able to demonstrate how, under a series of realistic conditions of demand uncertainty, it is profitable and advisable to apply multiskilling setups using k-chaining with k≥2. It was observed that the number of multiskilled employees needed grows as the demand variability increases. This is explained

because it is crucial to count on a strong organization and programing of multiskilled employees that will keep us prepared to cover the majority of attainable scenarios in the practice, and this is also why the resultant percentage of multiskilled employees with a 50% coefficient of variation in the demand is consequently of the 100%. Among some of the assumptions of the model, we suppose that the training cost is minimal and the productivity of an employee will be identical from one another and independent from the quantity of additional skills that he/she has been trained in. Nevertheless, the study shows that total multiskilling is not required to obtain maximum profits. Finally, the study also proves that k-chaining policies with $k \geq 2$ are convenient, especially when the demand variability levels are high.

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Heuristic methods for m-machine blocking flow shop with setup times to minimize hierarchical objective-function

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Abstract. In this article, heuristics methods are proposed for the sequence-dependent setup times m-machine blocking flow shop scheduling problem with hierarchical function of minimizing total completion time given that preventive total maintenance costs must be equal or lower than a certain value. A greedy randomized adaptive search procedure (GRASP), a discrete artificial bee colony algorithm (DABC) and a variable blocking insertion heuristic (VBIH) are adapted to minimize the hierarchical objective function. A procedure to assign PM operations is proposed to improve final solutions given by the adapted algorithms. All the methods were tested over a set of 11,520 problems. Computational results show that VBIH presented the best trade-off between effectiveness and efficiency. Additionally, statistical results show that the proposed procedure significantly improved solutions given by evaluated algorithms.

Keywords: scheduling, blocking flow shop, preventive maintenance, sequence dependent setup times, total completion time

1 Introduction

In most of m-machine flow shop scheduling problem literature, machines are considered always available to process jobs. Over the last years, some researches has been incorporated practical machines unavailability aspects to the scheduling problem (See e.g. [1] for a review of literature). Among machine availability constraints, this article focuses on preventive maintenance (PM) operations. Although job and PM activities scheduling are separately treated in literature, they are closely related to each other. While postponing processing of jobs to carry out a PM activity may delay the due date of jobs, the continuously processing of jobs may increase the probability of occurrence of a machine breakdown [2]. In flow shop scheduling problems, PM activity can be considered as fixed and known to a determined period ([3]) or flexible, i.e., it can be carried out inside an interval period T ([4], [5]). PM operations can also be modeled according to frequencies or PM statistical models ([2], [6]). In other cases, as in [7], [8], the

flow shop scheduling problem is integrated PM based on the condition of the machine.

Another common assumption in most of scheduling problems is the consideration of infinite capacity buffers. For reasons of technological restrictions, some production environments deals with the lack of intermediate storage between machines, a constraint known as blocking. This condition implies that, once the current job is finished, it must be kept on the current machine until the previous job is finished on the next machine. Thus, a blocking time is caused by the current job on the current machine until the previous job is finished and released from the following machine to the next. Examples of blocking flow shop can be seen in iron and steel industry, in the treatment of industrial waste and manufacture of metallic parts [9], in some stages of productive process as in concrete block production [10] or in robotic cells, where the job is kept on machine until it is picked it up by the robot to move it to the next stage [11]. A survey and a review of literature of the m-machine blocking flow shop scheduling problems can be seen in [12] and [13], respectively.

This article aims to propose heuristic methods for the sequence-dependent setup m-machine blocking flow shop with preventive maintenance based on machine deterioration condition to minimize total completion time (TCT) subject to total PM costs bound (PM_{cost}_B). The concept of PM based on machine deterioration condition was first presented by Bock et al. [14] in single machine scheduling problem. Recently, Yu and Seif [7] and [8] extended the aforementioned problem to blocking flow shop and no-wait flow shop, respectively, both adopting makespan minimization as objective-function. The measure considered in this article is known in literature as hierarchical function [15], where the target of the problem is to minimize TCT given that the total PM costs PM_{cost} must be lower or equal to a certain value. For the best of authors knowledge, this is the first article to study this problem.

The remaining sections are structured as follows: In Section 2, the problem is formally described and procedures to assign PM activities to job sequence are presented. Solution methods composed by a constructive heuristic and metaheuristics are proposed in Section 3. Section 4 shows the details of the computational experiments and the performance evaluation of the algorithms. Final considerations can be seen in Section 5.

2 Problem definition

The problem is stated as follows: a sequence of n jobs must be processed through m machines. All jobs follow the same pattern flow and the sequence established in the first machine is the same to the remaining machines. Operation of Job i has an associated processing time on machine j denoted as $p_{i,j}$. Setup time to prepare machine j to process job k after processing job i ($s_{j,i,k}$) is sequence-dependent and it is separated from the processing times. Preemption is not allowed. Release dates of all jobs are equal to zero. There are no buffers between subsequent machines, consequently, a finished job i on machine j must wait job

i-1 to be processed on machine j+1. Because of the absence of intermediate storage, job i is kept on machine j until job i-1 is finished and released from machine j+1. All machines are subject to preventive maintenance (PM) activities. PM actions are defined by level t ($t = 1, \ldots, l$), where each of them has an amount $ML_{t,j}^{max}$ available to process jobs. Figure 1 illustrates the considered problem. Deterioration rates, denoted as $\delta_{i,j,t}$ and $v_{j,i,k}^{t}$, is associated with processing and setup times of each job i, respectively.

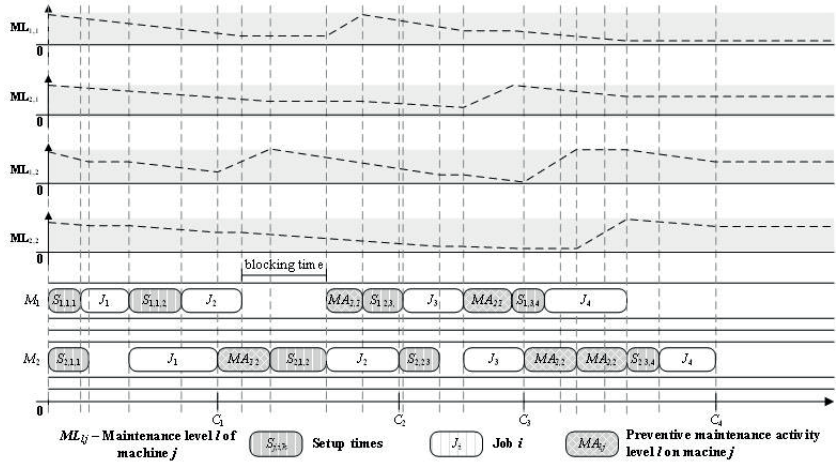

Fig. 1. 2-machine sequence-dependent blocking flow shop with 2 preventive maintenance levels

Deterioration level t of machine j before and after processing job k are denoted as $ML_{t,j,k}$ and $\overline{ML}_{t,j,k}$, respectively. Before the first job processed, each PM level t $ML_{t,j,1}$ is at its maximum, i.e., $ML_{t,j,1} = ML_{t,j}^{max}$. When job k is processed, being job i its adjacent, the value of $ML_{t,j,k}$ is updated with $\overline{ML}_{t,j,i}$ and the value of $\overline{ML}_{t,j,k}$ is equal to $ML_{t,j,k}$ - $p_{k,j} \times \delta_{k,j,t} + s_{j,i,k} \times v_{j,i,k}^{t}$. Each job is evaluated until $\overline{ML}_{t,j,k}$ reaches a value below zero, which indicates that $ML_{t,j,k}$ is insufficient to cover the next job k. In theory, a value of $\overline{ML}_{t,j,k} < 0$ means the occurrence of a machine breakdown. To prevent the failure, a PM level activity t on machine j with duration $MA_{t,j}$ is carried out before the processing of job that causes the negative value of PM level t of machine j to restore its condition to the maximum value, i.e., $ML_{t,j,k} = ML_{t,j}^{max}$). A PM activity t of machine j between adjacent jobs i and k is denoted as $MA_{j,i,k}^{t}$ and receives value $MA_{t,j}$ if $ML_{t,j} < 0$, and 0 otherwise. To ensure the feasibility of the problem, the quantity $(p_{i,j}) \times (\delta_{i,j,t}) + (s_{j,i,k}) \times (v_{j,i,k}^{t})$ must be less or equal than $ML_{t,j}^{max}$. Each PM activity of level t on machine j has an associated cost which is composed by the sum of all spare parts costs ($SP_{t,j}$) and workforce costs (WF_t) per unit of time (u.t.), i.e., $WF_t \times MA_{t,j}$. The total PM costs (PM_{cost}) corresponds to the sum of all PM activities carried out during the scheduling planning. The objective-function of the problem aims to minimize the sum of departure times of all jobs on the last machine, i.e. the sum of departure times ($\sum_{i=1}^{n} D_{i,m}$), given that the value of PM_cost must be equal or lower than a

certain value PM_{cost}_B. The computation of departure time of job assigned to position i on machine j ($D_{i,j}$) can be described as follows:

$$D_{1,j}=max\{D_{1,j-1};s_{j,1,1}\}+p_{1,j} \quad j=1,...,m \tag{1}$$

$$D_{i,1}=D_{i-1,2}+\sum_{t=1}^{l} MA_{j,i-1,i}^{t}+s_{j,i-1,i}+p_{i,1} \quad i=2,...,n \tag{2}$$

$$D_{i,j}=max\left\{D_{i,j-1};D_{i-1,j+1}+\sum_{t=1}^{l} MA_{j,i-1,i}^{t}+s_{j,i-1,i}\right\}+p_{i,j} \quad j=2,...,m-1 \quad i=2,...,n \tag{3}$$

$$D_{i,m}=max\left\{D_{i,m-1};D_{i-1,m}+\sum_{t=1}^{l} MA_{m,i-1,i}^{t}+s_{m,i-1,i}\right\}+p_{i,m} \quad i=2,...,n \tag{4}$$

Where $D_{1,0} = 0$. Since PM_{cost}_B is used as a constraint, the evaluation function accepts the candidate sequence π only if $PM_{cost}(\pi)$ is lower or equal the PM_{cost}_B and if $TCT(\pi)$ is lower than TCT of the current sequence ($TCT(\pi')$), as described on Alg. 1.

Algorithm 1: Evaluation procedure for solution quality

```
if PM_cost(π) ≤ PM_cost_B then
    if TCT(π) < TCT(π') then
        π' ← π;
    end
end
```

Since the m-machine blocking flow shop with TCT minimization scheduling problem is known as NP-Hard ([16]), the development of heuristic methods are feasible alternatives to solve the problem. In the next section, heuristic procedures to assign PM activities are proposed.

2.1 Procedure to assign preventive maintenance activities to job sequence

One of the aspects related with the jointly PM activities and jobs scheduling is how to integrate both activities. In this section two heuristics procedures are presented to incorporate PM activities to scheduling planning given a job sequence. The first procedure, proposed by [2], is applied to determine the total number of PM activities N_{PM} to maintain the m machines to process the n jobs and it is described as follows: When each job i is processed on machine j, the deterioration PM level t after processing job assigned to position i ($\overline{ML}_{t,j,[i]}$) is computed according to ($ML_{t,j,[i]}$ - $\upsilon_{j,q,}^{t}$ $\times$s$_{j,q,k}$ - $\delta_{k,j,t} \times p_{k,j}$). If $\overline{ML}_{t,j,[i]} < 0$, a PM activity with duration $MA_{t,j}$ is carried out before job assigned to position i, and $ML_{t,j,[i]}$ returns to $ML_{t,j}^{max}$ level. Otherwise, $ML_{t,j,[i+1]}$ receives $\overline{ML}_{t,j,[i]}$ and the next job is evaluated. The procedure is repeated until for all n jobs, considering each PM level of each machine.

The second procedure tries to improve the current sequence given by Ruiz's criterion. The local search, denominated $LS_{PM,RE}$ tries to reassign a PM activity to a prior position with the aim to minimize TCT without modify PM_{cost}. The

procedure starts the search setting the current sequence as candidate solution. Thus, $LS_{PM,RE}$ evaluates the possibility to move a given PM activity to a prior position regarding to its original position evaluating the minimization of TCT. Thus, $ML_{t,j,[k]}$ and $\overline{ML}_{t,j,[k]}$ are recalculated for all PM activities of level t of machine j, starting from the last $MA_{t,j}$. If $\overline{ML}_{t,j,[k]}$ generates a negative value when placed before job assigned to position k, originally placed prior before job that occupies position p, where k ¡ p, all positions between jobs k and p are evaluated and the sequence that generates the minimum TCT is hold. Next, the search continues with the last but one $MA_{t,j}$, which is evaluated from job k-1 until a prior job i, where k ¡ i that causes a negative value of $\overline{ML}_{t,j,[i]}$. In case of sequences with equal TCT, the sequence which $MA_{t,j}$ is placed to the most prior position is chosen. If a negative $\overline{ML}_{t,j,[k]}$ is caused by only one job, the procedure stops and the best sequence of the evaluation until then is kept as candidate solution. On the contrary, the procedure continues until the first PM activity of level t on machine j is evaluated. It is considered that the first PM activity is evaluated, if possible, from its original position until position between the first and second jobs. The best sequence found is retained as candidate solution. Thus, the next PM activity level t on machine j is evaluated. If TCT of best sequence found in the evaluation is lower than TCT of candidate solution, the new sequence becomes the candidate solution. The process is repeated until all l on all m machines are evaluated. If TCT of the best candidate sequence found is lower than TCT of the current sequence, the new one becomes the current sequence. $LS_{PM,RE}$ is repeated until no improvement is found. The criterion to evaluate the quality of solution of the sequences is described as follows: the procedure by Ruiz is used to generate the PM assignment of all sequences generated by all the methods. Then, $LS_{PM,RE}$ is applied only to final solution given by the proposed metaheuristics with the aim to minimize TCT.

3 Solution methods

Since the hierarchical function $TCT|PM_{cost}$ aims to minimize TCT given PM_{cost} bound, it is required to provide a total PM cost value bound (PM_{cost}_B). Here, the constructive method tPF-NEH(x), proposed by [17], is applied to generate initial sequence for all metaheuristics as well as to generate the PM_{cost}_B. For reasons of space, the description of tPF-NEH(x) will be omitted here. With some minor modifications, tPF-NEH(x) was adapted to the problem to minimize PM_{cost}. In order to minimize TCT, it is proposed the adaptation of recent metaheuristics designed for m-machine blocking flow shop with TCT minimization: GRASP-HPF2 by [18], VBIH by [17] and DABC_RCT by [19].

3.1 Greedy Randomized Adaptive Search Procedure

Ribas and Companys [18] proposed four versions of GRASP to minimize total completion time (TCT). Through experimental results, the author suggested the use of GRASP-HPF2 or GRASP-NHPF2. In this article, GRASP-HPF2 (Alg.

2) was adopted as an alternative to minimize $TCT|PM_{cost}\_B$. Basically, the proposed GRASP is composed by a construction phase and a local search phase, which is run until a specified stopping criterion is reached.

In the first iteration of the algorithm, solution given by tPF-NEH(x) is used as current candidate π'. From the second iteration on, the constructive phase uses HPF2 (see [18] for more details) to generate the current candidate solution π', using only TCT as objective-function. As in [18], the value of μ is randomly selected from a uniform distribution between $\mu(U[\mu_{min}; \mu_{max}])$ according to the size of the instance problem (see section 4 for more details). Additionally, the value of λ is set as 0. After construction phase, local search phase is applied to the candidate sequence. The local search consists of a Variable Neighborhood Search (VNS), composed by two neighborhood structures: swap (LS1) and insertion (LS2). In this phase, VNS aims to minimize TCT given that PM_{cost} is lower or equal to the best sequence found during its application. In LS1, each job of the sequence is randomly selected and swapped with all jobs that follows it in the sequence. If the best neighbor found (π) during VNS is better than the current solution π'', it becomes the new solution and the process continues until all jobs are evaluated. In LS2, each job of the sequence is removed from its original position and inserted into all other possible positions of the sequence.

Algorithm 2: Pseudocode of GRASP-HPF2

```
Input: π', π'' ← tPF-NEH(x)(π); λ; μ_min; μ_max; PM_cost_B;
repeat
    μ = μ_min + (μ_max − μ_min) × random(0,1);
    if iteration ≠ 1 then
        π' ← HPF2(λ, μ);
    end
    π' ← localSearch(π');
    if PM_cost(π') ≤ PM_cost_B then
        if TCT(π') ≤ TCT(π'') then
            π'' ← π';
        end
    end
until stopping_criterion is met;
Apply LS_PM,RE to π'';
Output: π'', TCT(π''), π''(LS_PM,RE),TCT(π''(LS_PM,RE)).
```

If the best neighbor π' is better than the current sequence π'', it becomes the new current solution π'' and the process continues until all jobs are evaluated. As in LS1, jobs are selected at random. The first neighborhood structure is randomly selected with a probability of 50%. After exploring a neighborhood through LS1 or LS2, the optimum local π' is compared with current solution π'''. If there is an improvement in TCT with PM_{cost} equal or lower than $PM_{cost}(pi''')$, pi''' is updated and the search continues in the other neighborhood. This process is repeated until pi'' is no longer improved. Finally, if the TCT of the local

optimum π' is better than the best solution found so far π'' with PM_{cost} lower or equal PM_{cost}_B, then π'' receives π'.

3.2 Discrete Artificial Bee Colony

In this article, the most effective version of DABC proposed by [19], named DABC_RCT, is adapted as solution method for the problem and its outline can be seen in Alg. 3.

Algorithm 3: Pseudocode of DABC_RCT

```
Input: N_f, N_TNO, tPF-NEH(x)(π);
Generate the initial population with N_f individuals through STR-1;
while stopping criterion is not met do
    π_best ← best solution of the population;
    π_worst ← worst solution of the population;
    Employed bees phase: for π_best and another randomly selected π
     of the population do
        for k ← 1 to t do
            Apply TNO procedure;
        end
    end
    Onlooker bees: Apply path relinking procedure to a randomly
     selected solution π of the population;
    Scout bees: Generate a new food source through HPF2;
    if PM_cost(π_new) ≤ PM_cost_B then
        if TCT(π_new) ¡ TCT(π_worst) then
            π_worst ← π_new;
        end
    end
end
Apply LS_PM,RE to π_best;
Output: π_best, TCT(π_best), π_best(LS_PM,RE), TCT(π_best(LS_PM,RE)).
```

The algorithm starts with the generation of a set of N_f initial solutions. This set of solutions represents the initial food sources that will be explored by employed bees. Each food source is represented by a permutation of jobs. The first individual is generated by tPF-NEH(x). The remaining individuals are generated by HPF2 according to the same range values of μ tested in GRASP-HPF2, using only TCT as evaluation criterion.

After the initialization, the best and worst individuals are chosen as follows: the solution generated by the best constructive heuristic is set as $PM_{cost\,B}$ and $TCT(\pi')$. π_{best} is set as the individual that obtains $PM_{cost} \leq PM_{cost}\_B$ and the minimum TCT of the population. The solution that obtains the worst PM_{cost} and TCT is chosen as π_{worst}. Next, the employed bees are sent to food source to evaluate their surroundings. In this phase, two employed bees are sent: the best one and another randomly selected from food source. In this phase, the Three

Neighborhood Operators (TNO) technique is used to enhance the exploration. TNO starts from randomly selecting two positions i and k, where $i < k$. In the following, three operators (See [19] for more details) are applied to the selected sequence and the best one among the three sequences generated is chosen, i.e., the sequence that generates both minimum PM_{cost} and TCT. This process is repeated N_{TNO} times. Next, the local search procedure used in GRASP-HPF2 is applied to the best obtained solution. If the new improved solution generates equal or lower PM_{cost} and lower TCT than the original sequence, then, the former replaces the latter. In the onlooker bee phase, a food source is established through information shared by the employed bees. In this phase, path relinking technique is applied. In this search process, the best sequence evaluated π', used as reference solution, and another picked up from the food source, used as the origin path π, are chosen. The path is built by interchanging moves with the aim to convert π into π'. Initially, both solutions are compared and jobs that are assigned to different positions in both sequences are detected. Next, the first job from π' assigned to a different position from π is interchanged with the job that are placed on that position. If the new solution generates lower or equal PM_{cost} and TCT lower than the original, it is kept. The process continues until π becomes equal to π'. If there are k jobs in different positions in π', k-1 movements are carried out, since the last one equals the reference sequence π. Thus, path relinking is carried out only if more than two jobs can be swapped. In the scout bee phase, a new food source is generated by HPF2 with the ranged values of μ. The new candidate solution (π_{new}) replaces the worst solution (π_{worst}) from the population only if the former is better than the latter, i.e., if $PM_{cost}(\pi_{new})$ $\leq PM_{cost}(\pi_{worst})$ and if $TCT(\pi_{new})$ ¡ $TCT(\pi_{worst})$. After scout bee phase, the procedure is repeated until a stopping criterion is met. As it will be seen in Section 4, besides the range values of μ, DAB_RCT has two parameters to be adjusted: The size of population (N_f) and number of iterations of TNO (N_{TNO}).

3.3 Variable Block Insertion Heuristic

Variable Block Insertion Heuristic (VBIH) was proposed by [17] to solve the m-machine blocking flow shop with TCT minimization. In VBIH, a block of jobs with initial size $bS = 1$ ($bS_{min} \leq bS \leq bS_{max}$) is removed from the current sequence π and it makes a mS_{max} number of block moves into the partial sequence, which is denoted as bIM(π,bS,mS_{max}). The best sequence amongst the mS_{max} generated goes under a Variable Local Search (VLS), which is composed by insertion and swap neighborhood structures with both guided by a reference sequence π^R. If the new sequence π'' generated by VLS is better than π, it replaces the current sequence. The size of bS continues the same as long as the sequence is improved. Otherwise, $bS \leftarrow bS + 1$ and a acceptance criterion based on simulated annealing is used to accept the inferior solution in order to escape from local minimum. This procedure is repeated until $bS \leftarrow bS_{max}$. Alg. 4 shows the outline of VBIH.

After $bS \leftarrow bS_{min} \leftarrow 1$, bIM() procedure is applied to sequence π. bIM() is a triplet-field that receives π, the size of block bS and the number of moves

mS_{max}. A block of jobs denoted as π_B with size bS are randomly selected and removed from the current sequence π. Then, each element from π_B is inserted into mS_{max} random positions of the partial solution π_p. The sequence π' that generates the minimum TCT and PM_{cost} is selected as the best sequence. The process is repeated until all jobs are from π_B are reinserted in π.

In the next phase of the algorithm, a Variable Local Search (VLS) is applied to solution given by bIM() π'. Referenced Insertion Search (RIS) and Referenced Swap Search (RSS) are employed as neighborhood structures LS1 and LS2, respectively. RIS tries to improve the solution, minimizing TCT with PM_{cost} lower or equals to $PM_{cost}(\pi')$, using a referenced sequence π^R which guides the procedure to choose the next job to be inserted. RSS tries to improve π' swapping job of position k to all other jobs of the sequence. A detailed description of VLS can be seen in [17].

Algorithm 4: Pseudocode of VBIH

```
Input: π‴, π^R ← tPF-NEH(x)(π); PM_cost_B; T;
while sopping_criterion is met do
    bS ← bS_min ← 1;
    while bS ≤ bS_max do
        π' ← bIM(π, bS, mS_max);
        π'' ← VLS(π^R, π');
        if PM_cost(π'') ≤ PM_cost_B then
            if TCT(π'') < TCT(π‴) then
                π, π‴, π^R ← π'';
            end
        else
            bS ← bS + 1;
            if PM_cost(π'') ≤ PM_cost_B then
                if r ¡ exp [(−TCT(π)−TCT(π''))/T] then
                    π ← π'';
                end
            end
        end
    end
end
Apply LS_PM,RE to π‴;
Output: π‴, TCT(π‴), π‴(LS_PM,RE),TCT(π‴(LS_PM,RE)).
```

After the local search phase, if TCT of new solution π'' is better than the current sequence π''', with $PM_{cost}(\pi'')$ is equal or lower than PM_{cost}_B, it becomes π'''. In the case of a worse TCT, but PM_{cost} lower or equals to PM_{cost}_B, the new sequence is accepted as incumbent sequence for the next iteration according to an acceptance criterion based on simulated annealing, described as $T = \tau\ P \times \frac{\sum_{i=1}^{n}\sum j=1^{m} p_{i,j}}{10\times n\times m}$, where τP is a parameter to be adjusted.

As shown in Alg. 4, a complete iteration of VBIH comprises the increment of $bS = 1$ until $bS = bS_{max}$. For the considered problem, it is noted that the mentioned process is highly costly in terms of computational time. In order to reduce computational efforts to adequate the method to the complexity of problem, an iteration is considered completed after the evaluation of π'' as current or incumbent solution, without considering the increase of bS.

4 Experimental results

The constructive and improvement heuristics were coded in Delphi 7. All experiments were performed in a PC Intel®Core(TM) i5-2500K CPU 3.30 GHz with 4 GB RAM under a 64 bits Windows 7 operating system. The PM interval duration of PM level t on machine j ($PM_{j,t}^{max}$) is established according to $PM_{j,t}^{max} = max(p_{i,j}) \times max(\delta_{i,j,t}) + max(s_{j,i,k}) \times max(\upsilon_{j,i,k}^{t})$.

Two instance problem datasets were generated to evaluate the performance of the methods. The first dataset, called adjustment parameter set are composed by $n = \{30,60,90,120,150\}$. The second, denominated medium and large size instance problems, is set as $n = \{10, 20, \ldots, 180\}$. In both sets, $m = \{5,10,15,20\}$, $l = \{1,2,3,5\}$ and setup duration = {10%, 50%, 100%, 125%} of the processing times. The specifications of the parameters generation can be seen in Table 1. For each combination between n, m, l and setup time rates, ten problems were generated. In total, 1,600 and 11,5200 problems were generated for parameter adjustment and large size instance problem data sets, respectively.

Table 1. Specification of parameters

Parameters	Specifications
Processing Times	[0, 99]; Random; Uniform Distribution, $i = 1, ..., n$; $j = 1, ..., m$
Setup times ($s_{i,j,k}$)	{10%; 50%; 75%; 125%} of the processing times i, $k = 1, ..., n$; $j = 1, ..., m$
Deterioration job rates	[0.1, 2] (One decimal place); Random; Uniform Distribution; $i = 1, ..., n$; $j = 1, ..., m$; $t = 1, ..., l$
Deterioration setup rates	[0.1, 2] (One decimal place); Random; Uniform Distribution; $i, k = 1, ..., n$; $j = 1, ..., m$; $t = 1, ..., l$
Workforce costs	WF_t = [500, 2,000]; Random; Uniform distribution; $t = 1, ..., l$
Spare Part costs	$SP_{j,t}$ = [1,000, 20,000]; Random; Uniform Distribution; $t = 1, ..., l$; $j = 1,..., m$

The effectiveness and efficiency of the algorithms were evaluated according to relative percentage deviation (RPD) and computational time. The relative percentage deviation (RPD) evaluates how much a given solution is far from the best solution found and is given by $RPD_{b,h,g} = 100 \times \frac{TCT_{g,b,h} - TCT_{best,b,h}}{TCT_{best,b,h}}$, where $RPD_{b,h,g}$ is the RPD of solution given by algorithm g for problem b of instance h, $TCT_{g,b,h}$ is the solution obtained by algorithm g for problem b of instance h and $TCT_{best,b,h}$ is the best solution found so far for problem b of instance h.

The stopping criterion of all metaheuristics was set according to three ranges of number of iterations (N_{it}): 40, 60 and 80. As each algorithm has different components, the CPU time of each N_{it} were recorded to evaluate the trade-off between quality of solution and computational time used. The efficiency of the methods were measured through average relative percentage computational time of algorithm g ($ARPT_g$), recently applied by [16], which is computed as $ARPT_g = \frac{\sum_{i=1}^{I} RPT_{i,h}}{I}$, where $RPT_{i,h} = \frac{T_{i,g} - ACT_i}{ACT_i}$ and $ACT_i = \frac{\sum_{g=1}^{G} T_{i,g}}{G}$, where

$RPT_{i,g}$ is the relative percentage computational time obtained by algorithm g for instance problem i, $T_{i,g}$ is the computational time of method g when applied to instance i, G is the number of algorithms considered, I is the number of instances of the database and ACT_i is the average computational times for instance i among all algorithms considered.

4.1 Computational performance evaluation

The IRACE software package [20] was applied to determine the parameters adjustment of all metaheuristics. For each algorithm, stop criterion was set as 80 iterations and IRACE was set with total number of experiments equals to 3,000. Parameter ranges $\mu(U[\mu_{min}; \mu_{max}])$ for GRASP-HPF2 and DABC_RCT were set as $\mu(U[0.1; 0.5])$ for $n \leq 30$, $\mu(U[0.2; 0.8])$ for $30 < n \leq 60$, $\mu(U[0.1; 0.5])$ for $60 < n \leq 90$, $\mu(U[0.2; 0.7])$ for $90 < n \leq 120$ and $\mu(U[0; 0.8])$ for $n > 120$. DABC_RCT was set with $N_f = 13$ and $N_{TNO} = 49$ and VBIH was set with $bS = 0.25$, $mS_{max} = 0.4$ and $\tau P = 0.9$. The performance of metaheuristics can be seen in Table 2. In order to measure the effectiveness of the proposed procedure, the solutions generated by GRASP-HPF2, DABC_RCT and VBIH through Ruiz PM assignment criterion is labeled as GRASP(N_{it})_S, DABC(N_{it})_S and VBIH(N_{it})_S. The application of $LS_{PM,RE}$ to the final solutions by GRASP(N_{it})_S, DABC(N_{it})_S and VBIH(N_{it})_S are labeled as GRASP(N_{it})_LS, DABC(N_{it})_LS and VBIH(N_{it})_LS. The CPU times of DABC_LS, GRASP_LS and VBIH_LS were obtained by the sum between the CPU time by DABC_RCT_S, GRASP_S and VBIH_S and the CPU time of $LS_{PM,RE}$ applied to each algorithm, respectively.

Regarding the quality of solution, in general, all versions DABC_RCT obtained the lowest mean RPD in comparison with all versions of GRASP-HPF2 and VBIH with the respective N_{it}. All versions of VBIH are competitive against DABC_RCT in quality of solution. On the other hand, GRASP(HPF2) presented the worst performance among the evaluated metaheuristics. Athough DABC_RCT presented the best performance in quality of solution, it is the algorithm that obtained the largest values of RPT, and consequently, CPU times.

Regarding N_{it}, all versions of VBIH are more efficient in comparison with GRASP-HPF2 and DABC_RCT. Figure 2 shows the means plot of the trade-off between ARPD $\times$ ARPT. The results indicated that VBIH(40)_S, VBIH(40)_LS, VBIH(60)_S, VBIH(60)_LS, DABC(80)_S and DABC(80)_LS obtained the best results. Additionally, the use of $LS_{PM,RE}$ improved the solutions given by DABC_S, GRASP(HPF2)_S and VBIH_S with a little increase in the mean ARPT. From the aforementioned algorithms, VBIH, in special VBIH(60)_LS seems to obtain the best trade-off between effectiveness and efficiency.

A non-parametric Kruskall-Wallis test was applied to statistically verify the performance of VBIH algorithms, DABC(80)_S and DABC(80)_LS, in order to evaluate the acceptance of the null hypothesis "H0 - the distribution of relative percentage deviation is the same across the evaluated algorithms". At a significance level of 5%, the Kruskall-Wallis test indicated the decision to reject the null hypothesis. The Dunn-Borrefoni *post hoc* analysis was conducted to evaluate a pairwise comparison between each evaluated to identify pair of algorithms

Table 2. Performance of the metaheuristics (best results highlighted in bold)

Method	n	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	Average
DABC(40)_LS	RPD	2.143	3.899	4.279	4.098	4.563	4.106	3.810	3.723	3.676	3.377	4.280	4.280	3.306	3.292	2.882	2.829	2.468	2.637	3.536
	RPT	0.335	0.143	0.084	0.048	0.029	0.017	0.013	0.020	0.008	-0.015	-0.010	-0.015	-0.016	-0.019	-0.018	-0.012	-0.006	-0.015	0.032
	CPU Time	0.208	0.987	2.829	6.299	12.005	20.804	33.266	50.915	72.424	100.053	135.956	178.671	230.520	294.006	367.546	445.638	543.590	658.736	175.247
DABC(40)_S	RPD	2.526	4.247	4.539	4.282	4.701	4.209	3.889	3.781	3.724	3.416	4.311	4.307	3.326	3.314	2.899	2.843	2.480	2.649	3.636
	RPT	0.328	0.139	0.082	0.046	0.028	0.016	0.013	0.019	0.008	-0.015	-0.010	-0.015	-0.017	-0.019	-0.018	-0.012	-0.006	-0.015	0.031
	CPU Time	0.207	0.982	2.820	6.287	11.991	20.788	33.249	50.896	72.404	100.030	135.932	178.646	230.494	293.978	367.516	445.608	543.558	658.700	175.227
DABC(60)_LS	RPD	1.804	3.123	3.340	3.447	3.700	3.345	3.366	3.100	3.127	2.993	3.820	3.741	2.789	2.755	2.399	2.427	2.043	2.067	2.966
	RPT	0.759	0.475	0.392	0.345	0.319	0.311	0.309	0.306	0.286	0.280	0.270	0.267	0.263	0.260	0.277	0.276	0.288	0.270	0.331
	CPU Time	0.276	1.277	3.636	8.116	15.356	26.959	43.160	65.607	93.249	131.503	176.293	232.769	300.880	380.303	483.367	580.295	712.074	853.039	228.231
DABC(60)_S	RPD	2.189	3.466	3.586	3.627	3.839	3.448	3.444	3.161	3.178	3.031	3.850	3.768	2.812	2.773	2.416	2.442	2.055	2.078	3.065
	RPT	0.752	0.471	0.390	0.344	0.318	0.311	0.309	0.306	0.286	0.280	0.270	0.267	0.263	0.260	0.277	0.276	0.288	0.270	0.330
	CPU Time	0.274	1.272	3.627	8.104	15.343	26.943	43.143	65.588	93.228	131.480	176.269	232.744	300.854	380.275	483.338	580.264	712.043	853.003	228.211
DABC(80)_LS	RPD	**1.323**	2.753	2.834	2.811	3.073	2.912	2.870	2.838	2.856	2.801	**3.415**	**3.372**	**2.390**	**2.362**	**2.120**	**2.187**	**1.927**	**1.869**	**2.595**
	RPT	1.328	0.913	0.797	0.737	0.705	0.704	0.707	0.690	0.658	0.680	0.650	0.651	0.648	0.639	0.677	0.666	0.688	0.660	0.733
	CPU Time	0.367	1.660	4.700	10.518	19.805	35.205	56.420	85.205	121.145	173.954	230.968	305.788	396.924	497.631	640.242	761.787	936.857	1115.903	299.727
DABC(80)_S	RPD	1.717	3.083	3.075	2.999	3.210	3.008	2.946	2.898	2.905	2.840	3.447	3.398	2.411	2.381	2.135	2.201	1.939	1.880	2.693
	RPT	1.320	0.909	0.795	0.736	0.704	0.703	0.706	0.689	0.658	0.680	0.650	0.651	0.648	0.639	0.677	0.665	0.688	0.660	0.732
	CPU Time	0.366	1.654	4.691	10.507	19.791	35.190	56.403	85.185	121.125	173.932	230.944	305.763	396.898	497.603	640.212	761.757	936.825	1115.867	299.706
GRASP(40)_LS	RPD	5.686	8.058	7.661	6.950	7.062	6.658	6.386	6.076	5.420	5.371	5.890	5.796	4.538	4.387	4.493	4.156	3.659	3.888	5.674
	RPT	-0.647	-0.533	-0.490	-0.472	-0.453	-0.447	-0.458	-0.448	-0.432	-0.443	-0.433	-0.424	-0.410	-0.418	-0.431	-0.424	-0.424	-0.419	-0.456
	CPU Time	0.056	0.403	1.340	3.202	6.440	11.554	18.041	28.368	41.551	58.522	81.068	109.006	146.108	185.121	225.923	273.508	340.236	422.950	108.522
GRASP(40)_S	RPD	6.121	8.432	7.933	7.149	7.206	6.767	6.470	6.143	5.472	5.415	5.924	5.825	4.562	4.407	4.509	4.171	3.671	3.899	5.782
	RPT	**-0.655**	**-0.537**	**-0.492**	**-0.473**	**-0.454**	-0.447	-0.459	-0.448	-0.432	-0.443	-0.433	-0.424	-0.410	-0.418	-0.432	-0.424	-0.424	-0.419	-0.457
	CPU Time	**0.054**	**0.398**	**1.331**	**3.191**	**6.426**	11.539	18.024	28.348	41.531	58.499	81.044	108.980	146.082	185.092	225.893	273.478	340.205	422.914	108.502
GRASP(60)_LS	RPD	5.665	7.920	7.562	6.871	6.810	6.679	6.284	5.752	5.111	5.209	5.722	5.676	4.266	4.347	4.331	4.099	3.706	3.699	5.539
	RPT	-0.458	-0.295	-0.249	-0.221	-0.204	-0.195	-0.196	-0.184	-0.155	-0.162	-0.149	-0.146	-0.127	-0.127	-0.149	-0.142	-0.157	-0.152	-0.193
	CPU Time	0.085	0.607	1.969	4.721	9.372	16.835	26.890	41.886	62.026	89.388	123.656	164.415	218.232	279.679	339.830	410.978	500.387	620.135	161.727
GRASP(60)_S	RPD	6.086	8.306	7.842	7.071	6.961	6.786	6.370	5.817	5.165	5.249	5.756	5.703	4.289	4.367	4.348	4.115	3.718	3.710	5.648
	RPT	-0.465	-0.299	-0.252	-0.222	-0.205	-0.196	-0.196	-0.184	-0.156	-0.162	-0.149	-0.146	-0.128	-0.128	-0.149	-0.142	-0.157	-0.152	-0.194
	CPU Time	0.083	0.601	1.960	4.709	9.358	16.819	26.873	41.867	62.006	89.366	123.632	164.390	218.206	279.651	339.800	410.947	500.356	620.099	161.707
GRASP(80)_LS	RPD	5.700	7.833	7.331	6.702	6.820	6.470	6.295	5.779	5.165	4.910	5.460	5.560	4.109	4.238	4.385	4.045	3.806	3.726	5.463
	RPT	-0.136	0.083	0.111	0.157	0.166	0.178	0.201	0.215	0.266	0.275	0.290	0.280	0.305	0.321	0.284	0.294	0.246	0.255	0.211
	CPU Time	0.133	0.928	2.909	7.009	13.709	24.678	40.349	62.291	93.353	137.763	190.452	250.709	329.464	427.101	516.176	625.544	744.461	923.997	243.946
GRASP(80)_S	RPD	6.117	8.225	7.600	6.895	6.973	6.580	6.381	5.841	5.218	4.951	5.494	5.591	4.133	4.259	4.401	4.061	3.818	3.737	5.571
	RPT	-0.143	0.079	0.109	0.155	0.165	0.177	0.201	0.214	0.266	0.275	0.289	0.280	0.305	0.321	0.284	0.294	0.246	0.255	0.210
	CPU Time	0.131	0.923	2.900	6.997	13.695	24.662	40.332	62.272	93.333	137.740	190.428	250.684	329.437	427.073	516.146	625.514	744.429	923.961	243.925
VBIH(40)_LS	RPD	2.162	3.468	3.834	3.884	4.035	4.020	4.008	3.800	3.734	3.742	4.281	4.428	3.660	3.528	3.546	3.281	3.041	2.955	3.634
	RPT	-0.609	-0.498	-0.464	-0.455	-0.451	-0.457	-0.466	-0.459	-0.464	-0.480	-0.468	-0.472	-0.481	-0.480	-0.489	-0.481	-0.482	-0.469	-0.479
	CPU Time	0.062	0.433	1.397	3.253	6.391	11.043	17.407	26.751	38.082	51.844	71.652	94.440	118.770	153.127	186.926	230.720	278.702	351.042	91.224
VBIH(40)_S	RPD	2.544	3.822	4.083	4.069	4.161	4.123	4.084	3.860	3.779	3.781	4.313	4.454	3.682	3.547	3.561	3.294	3.052	2.965	3.732
	RPT	-0.616	-0.503	-0.466	-0.456	-0.452	**-0.458**	**-0.466**	**-0.459**	**-0.465**	**-0.480**	**-0.468**	**-0.472**	**-0.481**	**-0.480**	**-0.489**	**-0.481**	**-0.482**	**-0.469**	**-0.480**
	CPU Time	0.060	0.427	1.388	3.241	6.378	**11.027**	**17.390**	**26.731**	**38.062**	**51.822**	**71.628**	**94.414**	**118.743**	**153.099**	**186.896**	**230.690**	**278.671**	**351.006**	**91.204**
VBIH(60)_LS	RPD	1.760	2.749	2.867	3.028	3.344	3.481	3.171	2.971	3.101	3.164	3.940	4.041	3.369	3.120	2.969	3.015	2.695	2.610	3.077
	RPT	-0.421	-0.290	-0.247	-0.233	-0.227	-0.230	-0.235	-0.240	-0.251	-0.250	-0.249	-0.249	-0.265	-0.264	-0.260	-0.262	-0.257	-0.244	-0.260
	CPU Time	0.092	0.615	1.967	4.609	8.973	15.831	25.082	38.006	54.244	76.397	103.430	137.187	173.153	219.458	276.004	333.627	407.592	503.190	132.192
VBIH(60)_S	RPD	2.164	3.084	3.101	3.206	3.475	3.579	3.243	3.027	3.147	3.205	3.972	4.069	3.390	3.140	2.984	3.027	2.707	2.620	3.174
	RPT	-0.429	-0.294	-0.249	-0.235	-0.227	-0.230	-0.236	-0.240	-0.251	-0.250	-0.249	-0.249	-0.266	-0.264	-0.260	-0.262	-0.257	-0.244	-0.261
	CPU Time	0.091	0.610	1.957	4.597	8.959	15.815	25.065	37.986	54.224	76.374	103.407	137.162	173.127	219.430	275.974	333.596	407.560	503.154	132.172
VBIH(80)_LS	RPD	1.493	**2.108**	**2.330**	**2.436**	**2.686**	**2.556**	**2.614**	**2.576**	**2.619**	**2.625**	3.822	3.489	3.032	2.671	3.012	2.785	2.474	2.529	2.659
	RPT	-0.118	0.021	0.076	0.101	0.120	0.122	0.127	0.101	0.084	0.116	0.098	0.107	0.085	0.087	0.110	0.085	0.104	0.114	0.086
	CPU Time	0.145	0.887	2.817	6.665	12.922	23.324	37.134	55.415	79.842	115.603	154.315	205.777	261.502	327.653	420.165	495.988	613.663	743.794	197.645
VBIH(80)_S	RPD	1.861	2.436	2.576	2.621	2.815	2.652	2.685	2.635	2.666	2.663	3.854	3.515	3.054	2.689	3.028	2.798	2.485	2.539	2.754
	RPT	-0.125	0.016	0.074	0.099	0.119	0.121	0.127	0.101	0.084	0.116	0.098	0.107	0.085	0.087	0.110	0.085	0.104	0.114	0.085
	CPU Time	0.144	0.881	2.808	6.653	12.909	23.308	37.117	55.396	79.822	115.580	154.291	205.752	261.475	327.625	420.135	495.958	613.632	743.757	197.625

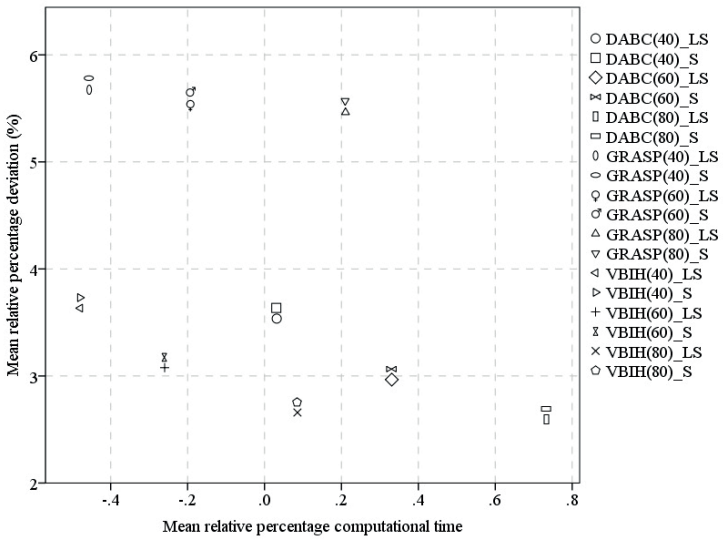

Fig. 2. Means plot of ARPT x ARPD of metaheuristics

Table 3. Krukall Wallis statistic test

Sample 1 × Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
DABC(80)_LS × VBIH(80)_LS	-1100.943	350.344	-3.142	0.002	0.060
DABC(80)_LS × DABC(80)_S	2895.059	350.344	-8.263	0.000	0.000
DABC(80)_LS × VBIH(80)_S	-4243.882	350.344	-12.113	0.000	0.000
DABC(80)_LS × VBIH(60)_LS	-5411.713	350.344	-15.447	0.000	0.000
DABC(80)_LS × VBIH(60)_S	-7974.157	350.344	-22.761	0.000	0.000
DABC(80)_LS × VBIH(40)_LS	-10239.820	350.344	-29.228	0.000	0.000
DABC(80)_LS × VBIH(40)_S	-12284.148	350.344	-35.063	0.000	0.000
VBIH(80)_LS × DABC(80)_S	1794.116	350.344	5.121	0.000	0.000
VBIH(80)_LS × VBIH(80)_S	-3142.939	350.344	-8.971	0.000	0.000
VBIH(80)_LS × VBIH(60)_LS	4310.770	350.344	12.304	0.000	0.000
VBIH(80)_LS × VBIH(60)_S	6873.214	350.344	19.619	0.000	0.000
VBIH(80)_LS × VBIH(40)_LS	9138.878	350.344	26.085	0.000	0.000
VBIH(80)_LS × VBIH(40)_S	11183.205	350.344	31.921	0.000	0.000
DABC(80)_S × VBIH(80)_S	-1348.823	350.344	-3.850	0.000	0.004
DABC(80)_S × VBIH(60)_LS	-2516.654	350.344	-7.183	0.000	0.000
DABC(80)_S × VBIH(60)_S	-5079.098	350.344	-14.497	0.000	0.000
DABC(80)_S × VBIH(40)_LS	-7344.762	350.344	-20.984	0.000	0.000
DABC(80)_S × VBIH(40)_S	-9389.089	350.344	-26.800	0.000	0.000
VBIH(80)_S × VBIH(60)_LS	1167.831	350.344	3.333	0.001	0.031
VBIH(80)_S × VBIH(60)_S	3730.276	350.344	10.647	0.000	0.000
VBIH(80)_S × VBIH(40)_LS	5994.939	350.344	17.114	0.000	0.000
VBIH(80)_S × VBIH(40)_S	8040.266	350.344	22.950	0.000	0.000
VBIH(60)_LS × VBIH(60)_S	-2562.444	350.344	-7.314	0.000	0.000
VBIH(60)_LS × VBIH(40)_LS	4828.108	350.344	13.781	0.000	0.000
VBIH(60)_LS × VBIH(40)_S	6872.435	350.344	19.616	0.000	0.000
VBIH(60)_S × VBIH(40)_LS	2265.663	350.344	6.467	0.000	0.000
VBIH(60)_S × VBIH(40)_S	4309.990	350.344	12.302	0.000	0.000
VBIH(40)_LS × VBIH(40)_S	-2044.327	350.344	-5.835	0.000	0.000

with different distributions of RPD. The results of the test can be seen in Table 3. The Dunn-Borrefoni *post hoc* analysis indicated that only DABC(80)_LS and VBIH(80)_LS presented an adjusted significance larger than 5%, which suggests that the null hypothesis cannot be rejected. Furthermore, Table 3 indicated significant statistical differences between VBIH(40)_LS, VBIH(60)_LS, VBIH(80)_LS and DABC(80)_LS and VBIH(40)_S, VBIH(60)_S, VBIH(80)_S and DABC(80)_S, respectively.

5 Final considerations

In this article, heuristic methods are proposed to solve the sequence-dependent setup times blocking flow shop with total completion time minimization given that total preventive maintenance costs (PM_{cost}) must be equal or lower than a certain value. Procedures to assign PM activities are proposed to minimize the objective-function. The constructive heuristic tPF-NEH(x) are adapted to provide PM_{cost} and initial sequence and the metaheuristics GRASP, DABC and VBIH are adapted to minimize $TCT|PM_{cost}B$. Experimental results show

that in the trade-off between quality of solution and computational time, VBIH, specially VBIH(60)_LS and VBIH(80)_LS, provided solutions with good quality in lower CPU time. Statistical analysis indicated that the developed procedure significantly improved the quality of solution given by the algorithms. Thus, the use of the procedure can be considered as part of the methodology to solve the problem. For future research, it is suggested the study and proposition of solution methods with the use of the procedure for the problem with other hierarchical function as makespan or total tardiness subject to PM_{cost}.

6 Acknowledgments

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Heuristics for earliness and tardiness scheduling of identical parallel machines subject to common restrictive due windows

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Abstract. This papers deals with the minimization of total weighted earliness and tardiness on identical parallel machines subject to common restrictive due windows. This problem is known to be NP-hard even for two machines. Since there is no reported solution procedure for instances with more than 40 jobs, we propose a family of fast heuristics, which are composed of four phases. First, jobs are sequenced according to priority rules. Second, jobs are assigned to machines using a greedy strategy. Third, a local search is performed to find a better distribution of jobs onto machines. Finally, two heuristics are applied for individually sequencing jobs in each machine, namely RN-RGH and RN-SEA. Results show that the algorithms based on RN-SEA consistently outperform the ones based on RN-RGH, however, with a cost of higher computing times.

Keywords: Scheduling, Identical parallel machines, Earliness and tardiness, Just-in-time, Heuristics

1 Introduction

Production scheduling problems have received an important attention from operational research practitioners for many years. However, traditional performance measures involve nondecreasing functions of jobs completion times, even though they neglect the costs that early jobs may incur [2]. The emergence of just-in-time (JIT) philosophy highlighted the importance of considering the cost structures associated with both earliness and tardiness (ET), which culminated in the rapid diffusion of nonregular performance measures. In many practical contexts, if a customer order goods from a supplier, a fixed delivery date is agreed upon. Commonly, the customer accepts a small deviation from this delivery date as there is an uncertainty degree on the supplier's side. This uncertainty may arise in different ways, such as machine breakdowns, resource availability, defects in raw materials, and other production issues. With that said, it may be suitable to negotiate a common due window. For a comprehensive survey of structural properties of related problems we refer to Rolim and Nagano [18].

To the best of our knowledge, Kramer and Lee [13] were the first to provide an extension from the single machine environment to multiple parallel machines when the due window is not restricted (the left boundary of the window may be greater than the sum of processing times) and the ET weights are job independent and asymmetric. They show that this problem is NP-hard even for the unit weight case and provide a pseudopolynomial-time dynamic programming algorithm for the 2-machine case as well as a heuristic with absolute error bound. The heuristic is extended for an arbitrary number of machines. The error tends to decrease if the number of jobs is reasonably large.

Chen and Lee [6] provide a branch-and-bound algorithm for the case when the due window is restrictive and the weights are job-dependent. Their algorithm is based on the column generation approach in which the problem is first formulated as a set partitioning type formulation and then, in each branch-and-bound iteration, the linear relaxation of this formulation is solved by the standard column generation procedure. Results are reported for instances with up to 40 jobs.

Mosheiov and Oron [15] consider the due window assignment problem with unit processing times in identical parallel machines. They show that this problem is solvable in $O(1)$ time and provide several properties of an optimal solution. In a similar problem, but with job-dependent ET weights and an additional penalty for due-window size, Mosheiov and Sarig [17] give an efficient solution procedure that runs in $O(n^4)$. Janiak et al [11] extended this problem by adding a penalty for the left boundary of the due window and established conditions for optimal schedules. Other special cases that require less computational efforts are described. Gerstl and Mosheiov [9] shows that the general problem discussed by Janiak et al [11] can be solved by a lower order algorithm in $O(n^3)$ with some improvements.

The case of uniform parallel machines with identical processing times is reported by Mosheiov and Sarig [16] where they show that the two-machine environment may be solved in constant time. Gerstl and Mosheiov [8] assume that the due window can be either restrictive or non-restrictive. It was also assumed that the ET weights are job dependent and the jobs share an identical unit processing time. With that said, they propose $O(3^m n^3)$ and $O(2^m n^3)$ algorithms for restrictive and non-restrictive settings, respectively.

Janiak et al [12] address the problem of due window assignment and scheduling when jobs have independent earliness and tardiness costs, and penalties are also incurred for due window size and location. They establish a number of properties of optimal solutions and derive dynamic programming algorithms, which are pseudopolynomial if the number of machines is considered to be constant.

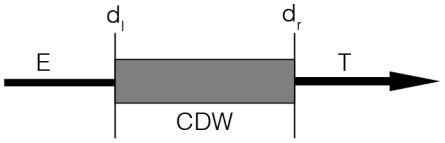
The main contribution of this paper is to propose alternative solution procedures to the problem defined by Chen and Lee [6] with an emphasis on computational efficiency. The only algorithm available in literature is reported to solve instances with up to 40 jobs in size. We show ten different heuristics to solve instances with up to 500 jobs and carry out extensive experiments to determine their performance. The remainder of this paper is divided as follows. Section 2 defines the problem and its structural properties. Then, in Section 3,

we describe phases 1 and 2 of the heuristics. Section 4 comprises the local search (phase 3). Section 5 is related to the sequencing aspects of each machine sub-problem (phase 4). We carry a discussion on the experimental results in Section 6 and, finally, Section 7 presents the concluding remarks as well as directions for further research.

2 Problem statement, definitions, and dominance properties

To a certain extent, the problem under study is similar to the one reported by Chen and Lee [6]. This problem consists of a set of n independent jobs, $N = \{1, 2, ..., n\}$, that need to be processed independently on any of the m ($m > 1$) identical parallel machines. The objective is to determine the sequence of all jobs so as to minimize the total weighted earliness and tardiness penalties. Using the well-known three field classification scheme introduced by Graham et al [10] and adapted by Rolim and Nagano [18] for scheduling problems with common due windows, the parallel machine scheduling problem (PMSP) can be expressed according to the notation $P|\langle \hat{d}_l, \hat{d}_r \rangle| \sum(\alpha_j E_j + \beta_j T_j)$, where $\langle \hat{d}_l, \hat{d}_r \rangle$ designates a common restrictive due window, that is, its left boundary must satisfy $d_l < \sum_{j=1}^{n} p_j$, E_j and T_j denote the earliness and tardiness of job $j \in N$, and α_j and β_j are job-dependent weights, respectively. A graphical representation of the due window is given in Fig. 1.

Fig. 1. Common due window representation



After being processed on the machine, and as a result of scheduling decisions, job j will be assigned a completion time denoted C_j. In other terms, the earliness and tardiness can be expressed as:

$$E_j = \max(d_l - C_j, 0) = (d_l - C_j)^+ \tag{1}$$

$$T_j = \max(C_j - d_r, 0) = (C_j - d_r)^+ \tag{2}$$

It is important to notice that, in contrast with tardiness penalties, earliness penalties are nonincreasing in C_j which makes the objective function a nonregular performance measure. For the common due window, let d_l and d_r be integers indicating the earliest and the latest due dates, respectively. Then, its size and location may be given as Eq. 3 and 4:

$$d_l = \lfloor h_l \times (\frac{\sum_{j=1}^{n} p_j}{m}) \rfloor \tag{3}$$

$$d_r = \lfloor h_r \times (\frac{\sum_{j=1}^{n} p_j}{m}) \rfloor \tag{4}$$

Here, h_l and h_r are given parameters for defining d_l and d_r, respectively. While the parameters h_l and h_r could be specified by any value, it is important to establish their ranges as $1 > h_r > h_l > 0$ so that the common due window becomes restricted by $0 < d_l < d_r < (\sum_{j=1}^{n} p_j/m)$. This configuration allows to avoid some trivial cases, for example, when $h_l = 0$ and $h_r = 1$ the common due window size would be, at least, close enough to $(\sum_{j=1}^{n} p_j/m)$, therefore, it could be possible to fit all jobs in the common due window. Moreover, if $h_l = h_r$, then the common due window could be reduced to a time instant, hence, no tolerance interval would exist, instead, it would be considered as a common due date. Other important assumptions are given as follows:

- All jobs are independent and ready at time zero.
- The machines can process only one job at a time.
- Jobs are processed without any interruptions, that is, machine breakdowns, planned or unexpected maintenance, and other effects that cause disruptions are not considered.
- The processing time of a given job is constant and cannot be compressed or expanded.
- No preemptions are permitted.

It is important to notice that the problem under study has some special characteristics that constitute optimal solutions. In a simplified way, these structural properties are given as follows:

- **Property 1**: There are no inserted idle times between jobs.
- **Property 2**: Jobs finishing before d_l are sequenced in nonincreasing order of the ratio p_j/α_j.
- **Property 3**: Jobs starting and finishing after d_r are sequenced in nondecreasing order of the ration p_j/β_j.
- **Property 4**: Jobs starting and finishing in the window can be sequenced in an arbitrary order.
- **Property 5**: In each machine, there exists an optimal schedule in which either the processing of the first job starts at time zero or one job is completed at d_l or d_r.

The proofs of these dominance rules can be found in Chen and Lee [6]. It is clear from properties 2, 3, and 4 that an optimal schedule follow the V-shaped property in each machine. Hereafter, the notations that will be used throughout the paper are established in Table 1.

It turns out that optimal schedules may have several different configurations. For this reason, we adopt the mapping procedure in Biskup and Feldmann [5] to

Table 1. Notations

Notation	Description
d_l	Left border of the common due window
d_r	Right border of the common due window
n	Number of jobs
m	Number of machines
j, k, l	Index of a job
i	Index of a machine
p_j	Processing time of job j
α_j	Earliness penalty of job j per time unit
β_j	Tardiness penalty of job j per time unit
E_j	Earliness of job j
T_j	Tardiness of job j
$s_{[l]}$	Leading idle time, i.e. starting time of the first job
C_j	Completion time of job j
S_j	Starting time of job j
J_E	Set of no-tardy jobs scheduled to finish before or in d_l, $J_E = \{j \vert C_j \leq d_l\}$
J_T	Set of tardy jobs scheduled to begin after or in d_r, $J_T = \{j \vert C_j - p_j \geq d_r\}$
J_W	Set of jobs that start and finish in the due window, $J_W = \{j \vert C_j - p_j \geq d_l \vee C_j \leq d_r\}$
s_l	Left-straddling job, $S_{s_l} < d_l \vee C_{s_l} > d_l$
s_r	Right-straddling job, $S_{s_r} < d_r \vee C_{s_r} > d_r$
s_d	Double-straddling job, $S_{s_d} < d_l \vee C_{s_d} > d_r$

guide the process of constructing a heuristic sequence. Despite the fact that an optimal schedule is V-shaped in each machine, it is essential to point out that it may contain one or two straddling jobs that are not necessarily subject to this property. We define a left-straddling job s_l if it straddles d_l, and right-straddling job s_r if it straddles d_r. Moreover, it is possible the existence of an optimal schedule with a double-straddling job s_d. In other words, a job that completely overlaps the common due window. From property 5, it also becomes evident that an optimal schedule might exist in which the first job does not start at time zero. We should call the time span before the starting of the first job as leading idle time.

3 Priority rules and greedy heuristic

Any algorithm designed for solving the PMSP with ET penalties subject to common due windows has two main decisions to address. The first one is how to assign jobs to machines, while the second concerns to the sequencing aspects on each individual machine. In this section, we establish a procedure devoted to find an initial schedule on each machine.

Rather than assigning each job to a machine without any predefined criteria, we decided to sort the jobs according to five different priority rules. These rules were established by Alvarez-Valdes et al [1] for a similar PMSP problem with

Algorithm 1: Greedy heuristic

```
1  Input: Initial job list (N) ;
2  Output: A schedule (π) ;
3  N ← {1, 2, ..., n}, M ← {M_1, M_2, ..., M_m}, flag ← true ;
4  Sort N according to one of the priority rules ;
5  while N ≠ ∅ do
6      if flag = true then
7          for i = 1 to m − 1 do
8              Let job in position [j] be the the first job in N ;
9              Assign job in position [j] to M_i ;
10             [j] ← [j + 1] ;
11         end
12         flag ← false ;
13     else
14         for i = 1 to m do
15             Insert jobs [j] and [j + 1] in every position of M_i ;
16             Save the best position in case of a minimum cost increase ;
17         end
18         Assign the job that produced the minimum cost increase to the best
             machine position ;
19         Update the first job of N ;
20     end
21 end
```

common due date. They tested several other rules, however, the following ones presented the best results:

- **Rule 1**: Nonincreasing $\beta_j p_j$.
- **Rule 2**: Nonincreasing $\beta_j p_j / \alpha_j$.
- **Rule 3**: Nonincreasing p_j.
- **Rule 4**: Nonincreasing β_j.
- **Rule 5**: Nondecreasing p_j / β_j.

Once the whole list of jobs is sorted, the jobs are assigned to each machine using a greedy heuristic. The first $m - 1$ jobs are distributed into the first $m - 1$ machines. Thereafter, the algorithm proceeds by promoting a competition between the next two jobs in the list. Calculations are made to determine in which machine and position the next two jobs attain a minimum cost increase. Then, the one that produces the minimum cost is assigned to the best position and the other is returned to the head of the list. The algorithm stops when the whole list is empty and the jobs are fully assigned to the machines. Algorithm 1 shows the pseudocode of the greedy heuristic.

4 Local search

The local search (LS) procedure was designed to exchange jobs between two machines that have different job charges. In other words, since the initial assignment do not consider the balance between earliness and tardiness penalties as well as processing times, LS looks for a decrease in the cost function by moving jobs from a machine to another. The following steps summarize the underlying idea of the LS and Algorithm 2 presents the pseudocode.

- Sort the machines in nonincreasing order of costs.
- Compute the total processing time (D_i^T), the sum of earliness penalties (α_i^T), and the sum of tardiness (β_i^T) penalties of each machine.
- Try to move all jobs $j \in M_i$ to all possible positions of M_{i+1} with a lower cost if at least one of the conditions holds: $D_i^T > D_{i+1}^T + p_j \vee \alpha_i^T > \alpha_{i+1}^T + \alpha_j \vee \beta_i^T > \beta_{i+1}^T + \beta_j$.
- If an improvement in the total cost is achieved, move job j from M_i to M_{i+1}.
- Repeat until all machines are tested.

Algorithm 2: Local Search

```
1  Input: Initial schedule (π) ;
2  Output: An improved schedule (π^new) ;
3  M ← {M_1, M_2, ..., M_m}, flag ← true ;
4  Sort the machines in nonincreasing order of costs ;
5  for i = 1 to m - 1 do
6      while flag = true do
7          Compute D_i^T, α_i^T, β_i^T, D_{i+1}^T, α_{i+1}^T, β_{i+1}^T ;
8          for all jobs j ∈ M_i do
9              if D_i^T > D_{i+1}^T + p_j ∨ α_i^T > α_{i+1}^T + α_j ∨ β_i^T > β_{i+1}^T + β_j then
10                 Try to move job j from M_i to M_{i+1} by inserting it in every
                    possible position ;
11                 Compute f(π^new) ;
12                 if f(π^new) < f(π) then
13                     Move job j to the best position in M_{i+1} ;
14                     flag ← true ;
15                 else
16                     Keep π unchanged ;
17                     flag ← false ;
18                 end
19             else
20                 flag ← false ;
21             end
22         end
23     end
24 end
```

5 Solving the single-machine subproblems

Once the jobs are distributed to machines, it is necessary to find better sequences on each machine. For this, two strategies are adopted: the RGH heuristic and SEA. Both deterministic methods are used to order the sequences on each machine. This is the third phase of the solution procedure. Hereafter, the nomenclature adopted to differentiate each solution procedure is RN-RGH and RN-SEA. Note that the nomenclature is followed by a number from 1 to 5, which distinguishes the 5 priority rules. The next two subsections describe these solutions procedures in detail.

5.1 RN-RGH

The RN-RGH algorithm is based on the procedure developed by Ying et al [20] for the single-machine problem with a common due window. The basic idea is to employ the constructive heuristic reported by these authors as an improvement method.

In a rather simplified manner, once the jobs are better distributed into the machines, their heuristic is applied in each machine separately. The algorithm starts by assigning the jobs that have high earliness and tardiness weights relative to their processing times to set J_W. Afterwards, from the remaining jobs, those which possess a high tardiness weight relative to the earliness weight are assigned to set J_E. Here, we omit the details of the algorithm due to space restrictions. For details and a numerical example we refer to Ying et al [20]. Again, their algorithm will be repeated in each machine and a new schedule will be constructed.

5.2 RN-SEA

The other improvement strategy is based on a Sequential Exchange Approach [14]. Here, a new heuristic is shown to schedule each machine against a common due window. Since there are three sets of jobs that constitute a solution for the problem (J_E, J_W, J_T), RN-SEA swaps or moves jobs between these sets systematically to derive a near-optimal solution. For the sake of simplicity, only two sets are considered since jobs in J_W may be sequenced in an arbitrary order. Now, let $J_{E'}$ denote the set of no-tardy jobs including the ones that start and finish in the due window ($J_{E'} = J_E \cup J_W$). Possible straddling jobs (s_l, s_r, and s_d) are also in $J_{E'}$ since they start processing before the right boundary of the due window.

For each machine, the jobs in $J_{E'}$ are selected one by one according to the sequence obtained as a result of phases one and two. This step is called forward exchange. The selected job $j \in J_{E'}$ is paired with all jobs in J_T to identify the swap which would lead to the largest improvement of the cost function value. Furthermore, job $k \in J_{E'}$ may move to J_T if this move leads to a greater improvement of the cost function than swapping jobs. If swapping the jth job in $J_{E'}$ with the lth job in J_T causes a better gain in the objective-function value than moving, the jth job in $J_{E'}$ and the lth job in J_T are swapped, while the

original sequences in $J_{E'}$ and J_T are maintained. On the other hand, if moving the kth job in $J_{E'}$ to J_T results in a best improvement than swapping, the kth job moves to J_T. After trying to swap or move all jobs in $J_{E'}$ to J_T, the best move is performed and the jobs are ordered according to the V-shaped property again.

The next step is called the backward exchange, which is similar to the forward exchange. However, jobs in J_T are selected one by one according to the sequence obtained from the previous step, and jobs are swapped with jobs in $J_{E'}$ to find the best improvement of the objective function value. Conversely, jobs in J_T are moved to $J_{E'}$ if the best improvement if a better gain is attained. After examining all the jobs in J_T to be swapped or moved to $J_{E'}$, the best move is performed and the final schedule is sequenced according to the V-shaped property once again.

Since the common due windows are restricted in relation to the total processing time, the start time of the first job to be scheduled is set to be zero. Evidently, for instances where the left boundary (d_l) has a larger restrictive factor (h_l), it may be the case that possible straddling jobs should be eliminated to obtain better objective function values, therefore, the procedure identifies them and produces backward-shift solutions of right and left straddling jobs. The start time is calculated as $s_{[l]} = d_l - S_{s_l}$ and $s_{[l]} = d_r - S_{s_r}$. Of course, jobs should be rearranged according to the V-shaped property and the solution with the best objective function value is kept.

6 Experimental results

Since there is no heuristic reported for the problem under consideration, a numerical analysis is conducted between the 10 proposed algorithms. The experiments were conducted on a personal computer with an Intel® Core i5 processor running at 3.7GHz, 16GB of RAM, and implemented in C++ programming language. The benchmark instances are available at the well-known OR Library [1] [3]. The short Pascal generator as well as the problem instances were proposed for the analogous common due date single machine problem [4].

Table 2. Instance configuration

Factors	Levels
n	20, 50, 100, 200, 500
m	2, 4, 6
(h_l, h_r)	(0.1, 0.2), (0.1, 0.3), (0.2, 0.5), (0.3, 0.4), (0.3, 0.5)
α_j	$U[1, 10]$
β_j	$U[1, 15]$
p_j	$U[1, 20]$

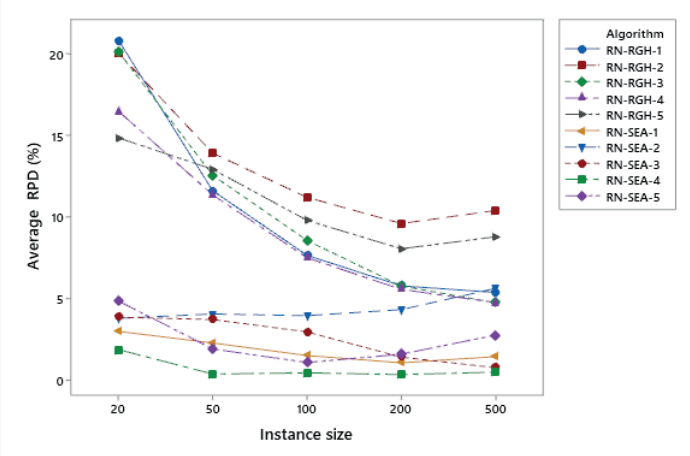
[1] http://people.brunel.ac.uk/~mastjjb/jeb/info.html

The characteristics of the test set are seen in Table 2. We used 10 different instances from 5 sizes, 3 machine configurations and 5 restriction factors combinations. Therefore, each algorithm solved a total of $10 \times 5 \times 3 \times 5 = 750$ instances. Two central performance measures were adopted, namely, the relative percentage deviation (RPD) from the best solution (see Eq. 5) and the computing times.

$$\text{RPD}(\%) = \frac{\text{obj}^{\text{heu}} - \text{obj}^{\text{best}}}{\text{obj}^{\text{best}}} \tag{5}$$

In Eq. 5, obj^{heu} stands for the solution achieved by one of the heuristics and obj^{best} refers to the best solution found from all the heuristic approaches. Of course, small values of RPD indicate better solutions. To demonstrate the performance of the heuristics, the average RPD values are compared based on three factors that modify the characteristics of the problem: instance size; window configuration; and number of machines. Fig. 2 shows the relationship between average RPD and the instance size.

Fig. 2. Estimated marginal means of RPD according to instance size



There is a clear difference between the initial assignment rules as well as the sequencing strategy adopted for solving the single-machine subproblems. Clearly, the best performance is achieved for rule 4 (nonincreasing β_j) When comparing the results for the same sequencing strategies, that is, between the 5 rules using the same sequencing algorithm (RN-RGH or RN-SEA), this rule outperforms the others for almost all instance sizes, except when combined with RN-RGH for solving instances with $n = 20$. Such an effect may be explained due to the nature of the data of the test set. Note that the individual tardiness penalty is allowed to be greater than the earliness penalty (refer to Table 2). In most practical contexts, contractual penalties incurred by a tardy job is usually higher

than the cost of maintaining an early job in the inventory. Other possible explanation of the success of this rule relies on the fact that due windows are tight in relation to the sum of processing times. Following this rationale, a larger number of jobs should be scheduled in J_T, therefore, the amount of tardiness penalties is expected to be greater than the amount of earliness penalties. In terms of the improvements methods applied to sequence jobs in each machine, RN-SEA presented a consistently better performance. The reason for this behaviour relates to the fact that RN-RGH might lead to poor results if there are many jobs with $\beta_j \gg \alpha_j$, where α_j is near to one and d_l is relatively small: in this situation, probably not all jobs with high tardiness penalties can be processed prior to the common due window and hence accumulate higher tardiness costs.

Table 3. Average RPD (%) values according to m and window configuration.

Algorithm	m			Window (h_l, h_r)				
	2	4	6	0.1-0.2	0.1-0.3	0.2-0.5	0.3-0.4	0.3-0.5
RN-RGH-1	7.537	11.056	12.189	3.936	6.813	15.819	10.953	13.785
RN-RGH-2	10.548	13.831	14.746	3.970	7.331	20.941	12.240	20.727
RN-RGH-3	7.304	11.152	12.636	4.113	7.085	16.476	10.345	13.801
RN-RGH-4	7.069	9.354	10.968	3.747	6.250	13.755	9.507	12.391
RN-RGH-5	8.395	11.436	12.828	4.375	6.511	15.304	12.484	15.757
RN-SEA-1	1.831	1.936	1.835	0.523	1.017	3.106	2.054	2.637
RN-SEA-2	4.354	4.310	4.414	0.741	1.509	5.988	4.723	8.836
RN-SEA-3	2.203	2.363	3.084	0.695	1.671	4.623	2.543	3.219
RN-SEA-4	0.747	0.622	0.683	0.423	0.347	0.668	0.750	1.232
RN-SEA-5	1.435	2.661	3.161	0.474	0.655	2.524	3.682	4.761

Table 3 presents the RPD values according to the number of machines and window configuration. It is clear that RN-SEA-4 outperforms the other constructive algorithms in almost all situations. Note that the distance between the RPD values for more restricted windows reduces due to the fact that only few jobs belong to J_W or finish without being penalized. For larger windows, RN-SEA also performs better since it is capable of systematically exchanging jobs between sets and, consequently, finding better solutions.

To understand the differences between the means shown in Fig. 2 and Table 3, we conducted an Analysis of Variance (ANOVA) with a confidence level $\alpha = 0.05$ and RPD was set as the dependent variable [19]. Two hypothesis were tested:

- **H0**: The means of RPD are the same across all methods.
- **H1**: There are differences between the RPD means across the methods

Since the results indicated that the significance value for the test was 0.00, it is possible to conclude that at least one mean of the distributions of the RPD is different, therefore, the null hypothesis can be rejected. We omit the details of the test due to space restrictions.

Then, we utilized the *post-hoc* Tukey HSD test to identify which groups had different means. The sample size is equivalent to 750 per algorithm (number of solved instances). The homogeneous subsets are reported in Table 4. It is worth noting that the algorithms are ordered in increasing order of the means, i.e., group 1 presents a smaller RPD mean in comparison with group 2 and so on. Observe that the last row of the table indicates the significance value for each subset. Taking subset 1 as an example, the significance value is 0.072 which is greater than 0.05, hence, there is not a strong evidence that there are differences between the means from this group (the null hypothesis cannot be rejected).

Table 4. Homogeneous subsets

Algorithm	Subset for $\alpha = 0.05$					
	1	2	3	4	5	6
RN-SEA-4	0.007					
RN-SEA-1	0.019	0.019				
RN-SEA-5		0.024				
RN-SEA-3		0.026				
RN-SEA-2			0.044			
RN-RGH-4				0.091		
RN-RGH-1				0.103	0.103	
RN-RGH-3					0.104	
RN-RGH-5					0.109	
RN-RGH-2						0.130
Sig.	0.072	0.764	1.000	0.104	0.845	1.000

Finally, other important measure refers to the computing efforts applied to obtain the solutions previously discussed. When the heuristics are compared in terms of the sequencing strategy on each machine, it is observed that the family of RN-RGH heuristics requires less computational effort in relation to RN-SEA. This type of behaviour occurs specially when the number of jobs exceeds 200, i.e., comparing two heuristics with the same initial assignment rules such as RN-RGH-3 and RN-SEA-3, it is seen that the average computing time of RN-RGH-3 for instances with 500 jobs is far inferior to the one in RN-SEA-3.

Moreover, as the number of machines increases, the computing times tend to decrease. Such a counter-intuitive result is also consistent with other studies in the same field [6, 7]. The cause of this effect may relate to the smaller number of jobs assigned to each machine, which may reduce the number of combinations tested by the heuristics. In contrast with the instance size and the number of machines, the window configuration does not seem to alter the computing times. Table 5 summarizes the average CPU times in seconds according to instance size and number of machines.

Table 5. Average CPU times in seconds (s)

Algorithm	n					m		
	20	50	100	200	500	2	4	6
RN-RGH-1	> 0.00	> 0.00	> 0.00	0.04	1.18	0.53	0.15	0.06
RN-RGH-2	> 0.00	> 0.00	> 0.00	0.06	1.91	0.87	0.24	0.09
RN-RGH-3	> 0.00	> 0.00	> 0.00	0.08	2.75	1.29	0.31	0.11
RN-RGH-4	> 0.00	> 0.00	> 0.00	0.04	0.75	0.33	0.10	0.05
RN-RGH-5	> 0.00	> 0.00	> 0.00	0.04	0.87	0.36	0.13	0.06
RN-SEA-1	> 0.00	> 0.00	0.03	0.73	37.57	20.63	1.90	0.47
RN-SEA-2	> 0.00	> 0.00	0.04	0.81	50.00	27.76	2.21	0.56
RN-SEA-3	> 0.00	> 0.00	0.05	1.10	79.96	45.31	2.76	0.60
RN-SEA-4	> 0.00	> 0.00	0.02	0.30	18.80	10.32	0.94	0.22
RN-SEA-5	> 0.00	> 0.00	0.01	0.09	3.41	1.72	0.28	0.11

7 Concluding remarks

In this paper, we have developed a family of ten heuristics for scheduling parallel machines subject to common restrictive due windows. The results were evaluated between the heuristics due to the fact that there is no other similar approach for the same problem. As a matter of fact, only Chen and Lee [6] proposed some exact solution procedures, however, they report that only instances with up to 40 jobs in size can be solved in reasonable time. Actually, their algorithms are quite complex and require a lot of implementation efforts from a computational perspective, therefore, our objective was to develop easy implementation algorithms capable of solving instances with up to 500 jobs in size. Our computational studies confirm that the most time consuming heuristic have an average CPU time of approximately 80 seconds, which confirms the possibility of application in practical contexts. In general, RN-SEA family has a better performance in relation to RN-RGH, however, higher CPU times are expected. For both RN-SEA and RN-RGH families, the fourth priority rule performs better, which can be justified according to the structure of the data used as a test set. Clearly, instances generated using a different range of values may benefit other priority rules.

One line of future research, would be to take advantage of designing parallel or cooperative algorithms. Moreover, a mathematical model could be implemented for solving small-sized instances. This way, further comparisons could be conducted with the heuristics shown in this paper and benchmarks reporting the lower bounds could be proposed. Another line of research would be the extension of this study to other related problems, such as the case of distinct due windows, sequence-dependent setup times, inclusion of release dates, different machine environments, etc.

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The Online Lot Streaming Problem: A Characterization and Solution Approach for Flexible Job Shop Environments.

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Abstract. The Online Lot Streaming (OLS) problem is introduced and tackled by a Constraint Programming (CP) approach. It is addressed at a Flexible Job Shop environment. In the OLS problem, lot streaming activities are performed dynamically and recursively, on an ongoing agenda. This is a novel approach, which differs from the predictive LS one. In this proposal, an OLS activity is also presented as a valid adaptive/reactive action. A test problem result is depicted to show the main characteristics of the solution.

Keywords: Online Scheduling, Lot Streaming, Rescheduling Problem.

1 Introduction to Online Lot Streaming Problem

The rescheduling problem and the lot streaming (LS) problem are two challenges that have received a lot of attention from the academic community and practitioners.

On the one hand, and so far, the reactive actions performed to adapt a disrupted schedule were implemented as tasks movements forward or backward in the agenda, tasks swaps or interchange, reallocation of resources to tasks, tasks cancelations and insertions, among the most usual ones (Vieira et al., 2003). On the other hand, contributions about the lot streaming problem, have addressed this activity as a predictive operational action, intended to split already dimensioned lots into smaller sublots, at the beginning of a given scheduling horizon. (Chan & Chiu, 2005).

In this work, a lot with an already defined and in-progress agenda, is enabled to be split downstream in the process, as a feasible reactive or adaptive action. In fact, the lot streaming as an allowed reactive action can be applied not only as a repair action to a disrupted agenda, but an adaptation action when the planned schedule underperforms.

The present approach is developed considering the scheduling as an online activity. Thus, scheduling activities are carried out considering a rolling horizon policy and using knowledge from the domain and the agenda status. Every time the MES concludes that the in-progress agenda needs an adaptation, it is carried out considering the current and known data coming from the shop floor. Here, a schedule adaptation refers to (i) a required rescheduling activity caused by an unexpected event, (ii) a

modification of the agenda caused by deviations from what has been planned, or, (iii) an action based on the chance of performance improvement. This work addresses the problem of lot streaming as an online activity. The *Online Lot Streaming* (OLS) problem is concerned with LS decisions, but performed dynamically on an ongoing agenda, over tasks that are planned or under execution when the LS activity is carried out. In this proposal, the OLS problem is tackled at flexible job shop environments.

2 An OLS Approach

The proposed approach requires the characterization of (i) the lot entity, (ii) the ongoing agenda features, and (iii) the OLS adaptive process. This enables a proper development of a constrained programming-based (CP) model, capable of addressing the ongoing situation being solved.

Characterization of lots. Lots *i* are associated with a single job or production order *j*, which elaborates a single product. The original sizes of the lots are defined upstream, at planning level by lot-sizing techniques (which differs from the operational LS problem), so they are known in advance. It is worth noting that, as online activity, lots are enabled to be divided during an ongoing agenda.

From the division of a lot, two or more sublots are created. For simplicity reasons, the sublots will be hereafter referred as lots too. The way they are generated and further divided during the process is represented by a tree structure. The *j* lots tree structure is neither predefined nor static, but dynamically generated for each lot during execution, when it is needed. Thus, the tree representation exists while there is at least one lot *i* being manufactured, associated with job *j.* Each lot *i* of *j* exists for a given period, called the lot *i* lifetime. A *j*'s lots tree is composed of any number of created lots, which were generated through time, during the manufacturing process, in order to complete all the operations required for all the parts belonging to the demanded job *j*.

It is considered that each lot has an identity on the schedule since it is created until it is further split or, until its manufacturing is completed, i.e. when a lot is divided, its existence ends, and new lots are created from it (see **¡Error! No se encuentra el origen de la referencia.**).

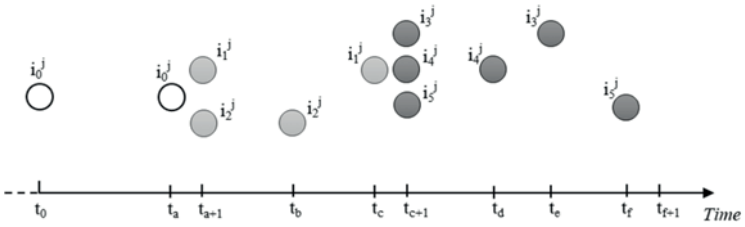

Fig. 1. Job *j* lots tree life representation. The lots i_1^j and i_2^j are child lots from their parent lot i_0^j.

The tree representation allows to identify the lots as: (i) *Original lot*, (ii) *Parent lots*, and (iii) *Child lots.* The child lots are created from a parent one and have a different identity than its parent. The proposed OLS differs from the problems classified as variable sublot, since in that case the sublot maintains its identity while it can vary its size during the planned agenda and there is no split during the schedule execution.

Ongoing agenda characterization. In the previous section, the dynamic behavior of lots were defined independently of the operations that they are planned to receive. However, there is a relation: when a lot *i* associated with a job *j* requires an operation *o*, a production task a is scheduled to accomplish that activity.

Each task *a* has its own attributes, which can vary over time. Each time t_c the agenda is observed, its status is captured; i.e. all entities belonging to the domain are asked for their attribute's current values. Afterwards, a classification is carried out.

Tasks & lots classification. At each t_c: (i) Tasks in the agenda are classified in already executed tasks, in progress tasks, and not yet executed tasks (Novas & Henning, 2010). The present proposal focuses on the in-progress tasks and the ones not executed yet. (ii) Lots are classified in those requiring to be divided (for instance, when an operation on a lot is interrupted), those that are enabled to split, but it is not a mandatory action, and the ones that are forbidden to be divided.

OLS process characterization. All features requiring to be addressed are identified, as well as all the preprocessing data activities. For instance, if a lot under an ongoing given operation was interrupted and requires to be divided, there will be parts belonging to that lot that still need the operation, and another number of parts that requires to schedule the next operation.

A CP model for the OLS. The proposal is presented as a constrained-based formulation, implemented as a Constraint Programming (CP) model, which was elaborated on the IBM ILOG CPLEX Optimization Studio. The approach is based on the CP model presented in Novas (2019) for the LS & Scheduling problem and extended for the OLS. Constraints and expressions are classified in those required to capture the domain status at a given time point, the ones linked to the adaptive action, and those to schedule and optimize. The complete model is not presented here because of the lack of space.

3 A Test Case Study

Here, a single example is depicted for illustrative purposes. An ongoing agenda in a 5 machines FJS, is under execution: 3 jobs, 3 operations per job, 2 lots for *j*1, 3 lots for *j*2 and *j*3 (Fig. 2 (a)). At time t_c =2500 s, the agenda is revised for 100 *s*. As it can be observed in Fig. 2(b), at t_u =2600, a new schedule is proposed for the rest of the schedule horizon. Fig. 2(c) shows the lots tree of *j*3 observed once the complete number of parts demanded by *j*3 is finished.

The split at t_c of several lots, results in a new agenda from t_u, which reaches a better makespan than the original one (original mk=6785; new mk=6535). These results illustrate how the OLS as a reactive/adaptive action can also be a powerful tool to dynamically improve the performance of an ongoing agenda.

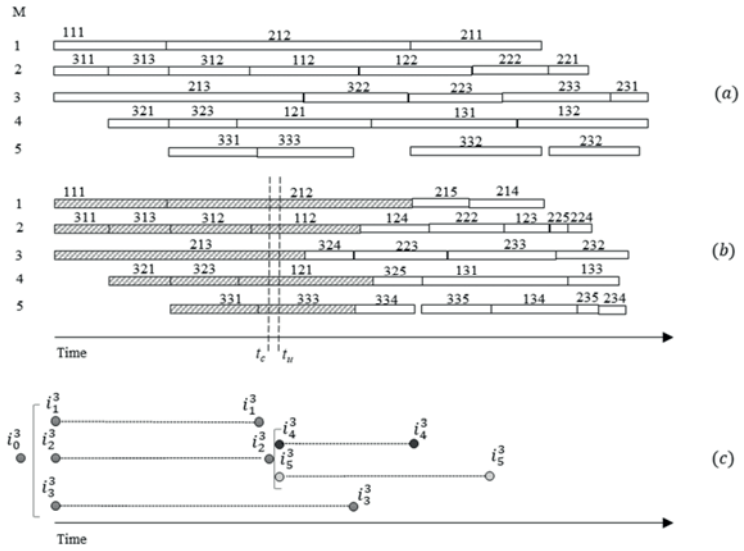

Fig. 2. (a) Gantt chart depicting the predictive ongoing agenda. Tasks' labels represent the job, operation and lot numbers. (b) New agenda for remaining tasks from t_u. (c) The job $j3$ lots' tree.

4 Conclusions

The Online Lot Streaming (OLS) problem was introduced for the first time and an approach to characterize it was proposed. The main features describing the OLS problem were presented and a CP model was developed to solve it. An illustrative example is depicted.

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Uso de la Programación por Metas y del Proceso Analítico de Jerarquías para la obtención de la mezcla de productos

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Resumen. En este trabajo se propone una metodología que integra a la Programación por Metas Ponderadas con el Proceso Analítico de Jerarquías para la obtención de la mezcla de productos, en un sistema de múltiples cuellos de botella. Se aborda el problema analizando un caso adaptado de una empresa que fabrica 4 productos que deben pasar por 6 estaciones de trabajo. Se considera la opinión de 4 expertos involucrados en la decisión y se plantean metas que consideran maximización del beneficio, la explotación de los recursos cuellos de botella y la satisfacción del cliente. La priorización de dichos objetivos se obtiene a través del Proceso Analítico de Jerarquías, donde se agrega la opinión de los expertos y se obtiene un único vector, que se transforma en las ponderaciones de las metas. El resultado es una mezcla de producción que satisface las metas, en forma correspondiente a la opinión de los expertos.

Palabras Clave: Programación por Metas. Proceso Analítico de Jerarquías. Juicios Agregados.

1 Introducción

En trabajos anteriores se ha analizado el caso de una empresa cuyo sistema de producción tenía una capacidad tal que no lograba satisfacer la totalidad de la demanda pronosticada [1]. Para la resolución del mismo se planteó en principio el clásico modelo de programación lineal. Este modelo arrojó una mezcla para la cual se obtuvo el máximo beneficio. Pero como suele suceder, al momento de realizar la planificación de la producción el decisor puede tener que considerar otros objetivos, además, de obtener el máximo beneficio. Estos objetivos pueden estar ligados a las prioridades competitivas, a eventualidades propias del sistema de producción tales como la disminución del rendimiento de alguno de los recursos, entre otros. En dicho estudio, se propuso la aplicación de un modelo de Programación por Metas Ponderadas que brindó flexibilidad, permitiendo acercarse a una solución que se ajustó mejor al entorno del sistema. Dicha solución varió en función del peso o ponderación que se les otorgó a las variables de desviación. Este resultado permitió comprender que si estas ponderaciones están debidamente sustentadas la solución se puede considerar mucho más sólida.

En el presente trabajo, se propone aplicar una metodología para tomar la decisión de obtener la mezcla de productos, que permita alcanzar varios objetivos, en función de lo que se considere prioritario, siendo esta prioridad definida a partir de la aplicación del proceso Analítico de Jerarquías.

La estructura del trabajo es la siguiente:

En la próxima sección se presenta el marco teórico y la revisión bibliográfica que permitieron el análisis y propuesta de una metodología válida a la problemática planteada.

En la sección de desarrollo se presentan las principales características de la organización tales como relevamiento del proceso, recursos de la producción, costos y demanda pronosticada. A partir de los mismos se prueba la metodología propuesta y se plantean las soluciones halladas.

Finalmente se hace un análisis de resultados y conclusiones.

2 Marco Teórico

La Programación por Metas (PM) fue propuesta por Charnes y Cooper en 1961 como un método sencillo para resolver los problemas lineales de programación multiobjetivo que eran infactibles. Desde entonces se han desarrollado numerosos trabajos que abordan tanto los aspectos teóricos como los operativos de la técnica, abarcando un amplio campo de aplicación [2].

La PM es para Tamiz, Jones y Romero [3] "una metodología flexible y pragmática especialmente adecuada para resolver problemas con variables decisionales complejas en los que diversos objetivos al igual que muchas de las variables y de las restricciones, están involucrados".

Buscar lo "aceptable" antes que lo "óptimo" constituye el lema de esta técnica, siendo su objetivo final llegar a encontrar una solución que satisfaga las necesidades. Filosóficamente la PM se apoya en el concepto de soluciones "satisfacientes", introducido por Herbert Simon [4]. El término satisfaciente intenta fusionar los términos "satisfactorio" y "suficiente" [5]. En otras palabras, el decisor intenta obtener una solución que se aproxime, en lo posible, a unos niveles de satisfacción denominados "niveles de aspiración" que han sido prefijados de antemano para cada uno de los objetivos. La "mejor" solución, (solución satisfaciente), se define en PM como aquélla que minimiza las desviaciones no deseadas del conjunto de objetivos o niveles de aspiración.

2.1 Estructura formal de los modelos de PM

Los objetivos múltiples y en conflicto, las restricciones y las metas son elementos característicos de los modelos de PM. Dentro de este contexto, las "metas" representan las restricciones no rigurosas que el decisor desea que se satisfagan, pero que al mismo tiempo pueden ser violadas en caso de no existir puntos que las verifiquen, considerándose a estas soluciones como admisibles.

En PM los objetivos se transforman en restricciones meta, las que se añaden al conjunto de restricciones fijas, propias del sistema. Las restricciones meta representan limitaciones no rigurosas, debido a que el nivel de aspiración deseado puede ser o no

alcanzado. Para ello, se precisa introducir variables de desviación positivas (p_i) y negativas (n_i), que midan en cada instante el exceso o la falta de cumplimiento de cada meta con respecto al nivel de aspiración deseado.

Para tratar de alcanzar el nivel de logro requerido se debe minimizar una función de las desviaciones no deseadas. A este arreglo se lo denomina funcional. Una variable de desviación se dice no deseada cuando se necesita que alcance su valor más pequeño, preferentemente cero. Se pueden presentar tres posibilidades:

- La meta debe alcanzar el mayor nivel de aspiración de un atributo, $f_i(x) \geq t_i$. En este caso la variable no deseada será la n_i.
- La meta espera el menor valor de un atributo, $f_i(x) \leq t_i$. En este caso la variable no deseada será la p_i.
- La meta pretende alcanzar exactamente el nivel de aspiración, $f_i(x) = t_i$ las variables no deseadas son n_i y p_i.

La estructura general de un modelo de PM con "q" metas, "m-q" restricciones del sistema o restricciones técnicas y "n" variables decisionales se presenta en Ecuaciones 1 a 4 [6], [7]:

Modelo General de PM

Función de logro

$$\min Z = g(n_i, p_i) \tag{1}$$

Sujeto a:

$$f_i(x) + n_i - p_i = t_i \quad \forall\, i \in \{1, \ldots, q\} \quad (\text{metas}) \tag{2}$$

$$h_i(x) \leq b_i \quad \forall\, i \in \{q+1, \ldots, m\} \quad (\text{restricciones}) \tag{3}$$

$$x, n_i, p_i \geq 0 \tag{4}$$

Donde:

n_i, p_i = desviaciones negativas y positivas, que cuantifican la falta o exceso de logro respectivamente;

$X = (x_1, x_2, \ldots, x_j) \in \Re n$ vector de variables de decisión

t_i = nivel de aspiración asociado al atributo i-ésimo.

En Ecuación 5 se representa la expresión matemática de $f_i(x)$ o $h_i(x)$

$$f_i(x) \text{ o } h_i(x) = \sum_{j=1}^{n} a_{ij}\, x_j \quad \forall\, j \in \{1, \ldots, n\} \tag{5}$$

Las variables de desviación negativa (n_i) y positiva (p_i) de la meta i-ésima están definidas algebraicamente en Ecuaciones 6 y 7:

$$p_i = \max\{0, f_i(x) - t_i\} \quad \text{ó} \tag{6}$$

$$p_i = \frac{1}{2}[|f_i(x) - t_i| + f_i(x) - t_i]$$

$$n_i = \max\{0, t_i - f_i(x)\} \quad \text{ó} \tag{7}$$

$$n_i = \frac{1}{2}[|f_i(x) - t_i| + t_i - f_i(x)]$$

De acuerdo con Tamiz, Jones y El-Darzi [8], Ignizio y Romero [9] y Romero [10], la función de logro detallada en ecuación 1, puede tomar diferentes configuraciones, dando origen a distintos modelos de PM. Entre los modelos más tradicionales, se pueden mencionar los siguientes:

(i) minimizar la suma ponderada de todas las desviaciones no deseadas en forma simultánea, llamado Programación por Metas Ponderadas;

(ii) minimizar las desviaciones no deseadas por orden de importancia y en un sentido lexicográfico, denominado Programación por Metas Lexicográficas;

(iii) minimizar únicamente la desviación más grande en el sentido min-max, conocido como Programación por Metas Minimax o Chebyshev.

En la próxima sección, se desarrolla brevemente el modelo mencionado en i) dado que es el que aplica a la metodología propuesta.

Programación por Metas Ponderadas (PMP)

La PMP también conocida como programación por metas arquimediana, busca minimizar el logro agregando las metas en una única función. Para este caso la ecuación 1 queda determinada por la Ecuación 9. Las ecuaciones 2 a 4 correspondientes a las restricciones, presentadas en el modelo general, no sufren modificaciones [7]

$$min\left(\sum_{1=1}^{q} \alpha_i\, n_i + \beta_i p_i\right) \tag{8}$$

Siendo:

$\alpha_i = w_i/k_i$, si n_i es no deseada; en caso contrario $\alpha_i = 0$;

$\beta_i = w_i/k_i$, si p_i es no deseada; en caso contrario $\beta_i = 0$;

w_i = pesos de ponderación o de preferencia;

k_i = constantes de normalización

Los pesos w_i permiten diferenciar los distintos objetivos en orden de importancia; valores mayores representan metas más importantes.

Los objetivos inconmensurables deben ser tratados en términos de una misma unidad de medida. Por ello, es necesario afectarlos por una constante de normalización. Se pueden emplear diferentes constantes de normalización, las más utilizadas son:

- El valor objetivo o target $k_i = t_i$, (no es aplicable cuando los objetivos son cero)
- La norma Euclideana, de los coeficientes técnicos del objetivo a_{ij} (ver Ecuación 9)

$$k_i = \sqrt{\sum_j {a_{ij}}^2} \tag{9}$$

- La sumatoria de los valores absolutos de los coeficientes técnicos del objetivo (ver Ecuación 10)

$$k_i = \sum_j |a_{ij}| \tag{4}$$

El Proceso Analítico de Jerarquías.

El Proceso Analítico de Jerarquías (PAJ) (o AHP, Analytic Hierarchy Process), desarrollado por Thomas L. Saaty, [11] está diseñado para resolver problemas complejos que tienen criterios múltiples.

Es un método de trabajo sencillo, lógico y estructurado, basado en la descomposición del problema en una estructura jerárquica.

Parte del proceso requiere que quien toma las decisiones proporcione evaluaciones objetivas y/o subjetivas respecto a la importancia relativa de cada uno de los criterios que se seguirán para tomar la decisión. Se utilizan matrices de comparaciones pareadas para establecer dichas preferencias. Las comparaciones pareadas son las bases fundamentales del PAJ. Se emplea la escala de Saaty con valores de 1 a 9, como se muestra en Tabla 1, para calificar las preferencias relativas de los elementos. A través de un desarrollo matemático se calculan los vectores de prioridades.

Tabla 1. Escala de Saaty.

Planteamiento verbal de la preferencia	Calificación Numérica
Extremadamente preferible	9
Entre muy fuertemente y extremadamente preferible	8
Muy fuertemente preferible	7
Entre fuertemente y muy fuertemente preferible	6
Fuertemente preferible	5
Entre moderadamente y fuertemente preferible	4
Moderadamente preferible	3
Entre igualmente y moderadamente preferible	2
Igualmente preferible	1

Una consideración importante en términos de la calidad de decisión final se refiere a la consistencia de juicios que muestra el tomador de decisiones en el transcurso de la serie de comparaciones pareadas. La consistencia perfecta es difícil de lograr ya que los juicios son realizados por personas. Esta metodología calcula la relación o razón de consistencia de Saaty, RC, considerando aceptable los valores menores a 0,1. Si el grado de consistencia es aceptable, puede continuarse con el proceso de decisión. Si dicho grado es inaceptable, quien toma las decisiones debe reconsiderar y modificar sus juicios sobre las comparaciones pareadas antes de continuar con el análisis. Este procedimiento asegura la no existencia de inconsistencias en la emisión de juicios.

Otra consideración, también de suma importancia, es que esta metodología permite la introducción de juicios de los diversos actores que pudieran intervenir en la decisión. Cuando se plantean los juicios de dos o más expertos, existen básicamente dos modos filosóficos distintos de agregar la información individual. La elección va a depender si el grupo quiere actuar en conjunto o en forma separada, Forman y Peniwati [12]. Uno de los modos consiste en trabajar con el grupo en conjunto formando uno nuevo a partir

de la agregación de los juicios individuales (AIJ) en cada nivel de la jerarquía. Esto produce la pérdida tanto de identidad como de las preferencias individuales de los participantes a favor de una combinación sinérgica, que actúa como única. Dicha combinación debe satisfacer la condición de reciprocidad de los juicios. Saaty [11] propone la utilización de la media geométrica como la única forma de sintetizar en un solo juicio representativo las opiniones de todos los participantes en la toma de decisiones.

El otro modo, es cuando los participantes actuando en forma separada con distintas valoraciones del sistema, desean mantener su independencia e identidad. En este contexto, el proceso de agregación se realiza al final, una vez obtenidas las prioridades individuales (AIP). Dicha combinación se puede realizar tanto a través de la media aritmética (representativa de un intervalo promedio) o media geométrica (representativa de un cociente promedio). Forman y Peniwati [12] sostienen que la media geométrica es una medida consistente, ya que en el PAJ se utilizan escalas de razón, donde se evalúa cuantas veces es más preferible una alternativa frente a otra.

2.2 Metodología propuesta

A partir de los datos de la empresa se evalúan los objetivos que se desean cumplir, en función del entorno de la organización. Utilizando el Proceso Analítico de Jerarquías, se obtiene el vector de prioridades que sintetiza la opinión agregada de 4 expertos, en forma sistemática. Las preferencias representan la importancia relativa que tienen los objetivos considerados.

Este vector resultante, se ingresa en el modelo de programación por metas como la ponderación de las desviaciones, afectando de esta forma la composición de la mezcla.

Se utiliza Excel y su complemento Solver, tanto para PAJ como para la programación por metas.

Cabe destacar que los datos reales se adecuaron para explicar con mayor claridad la metodología propuesta.

3 Desarrollo

En la siguiente sección, se presentan las principales características técnico-económicas de la organización. Seguidamente se plantea como primera alternativa de mezcla de producción a la solución que es arrojada por el modelo de Programación Lineal. Los resultados de este modelo, que en cierta forma revelan el comportamiento del sistema de producción ante la demanda impuesta, son sometidos a juicio de los distintos departamentos involucrados en la decisión. Como consecuencia, ~~se~~ proponen diversos objetivos a cumplir por la solución buscada.

Estos objetivos son evaluados por los expertos de cada departamento, aplicando el Procesos Analítico de Jerarquías, generándose una matriz de comparaciones pareadas para cada uno de ellos. Se utiliza la agregación de los juicios individuales, AIJ, a efectos de integrar todas las opiniones en un único vector.

Finalmente, los resultados de este proceso se introducen en el modelo de Programación por Metas Ponderadas.

3.1 Descripción de la organización

La empresa fabrica y vende 4 productos, denominados X_1, X_2, X_3 y X_4.

En la Tabla 2 se detallan los procesos que se desarrollan como así también los medios de transporte interno utilizados para llevar los materiales de un sector a otro:

Tabla 2. Procesos de obtención de los productos.

Operación	Proceso	Transporte interno
1	Descarga	Autoelevador
2	Almacenamiento	Autoelevador a estanterías
3	Ensamble	Carro manual a puesto ensamble
4	Pintura	Carro manual a puesto pintura
5	Empaque	Riel de ganchos a sector empaque
6	Despacho	Autoelevador

Características técnico-económicas del sistema

En la Tabla 3, se muestran los datos brindados por el área de Finanzas, referidos al costo y beneficio unitario, como así también aquellos provenientes del área de Comercialización, en este caso, precio de venta y demanda proyectada.

Tabla 3. Datos de Comercialización y Finanzas

	X_1	X_2	X_3	X_4
PV	1850	1730	1950	1600
Costo [$/u]	1.011,25	844,13	870	1.147,5
Beneficio [$/u]	838,75	885,88	1080	452,5
Demanda [u/mes]	800	450	500	600
Beneficio total [$/mes]	671.000	398.643,75	540.000	271.500

Se espera un beneficio total de $1.881.143,75, si se fabrica toda la demanda.

En Tabla 4 se presentan las capacidades de las actividades correspondiente al sistema de operaciones de la organización y en la Tabla 5 los requerimientos por producto.

Tabla 4. Capacidad de las actividades.

Actividad	N° de operarios	h/mes
DESCARGA (DC)	4	640
ALMACENAMIENTO (AL)	1	160
ENSAMBLE(EN)	12	1920
PINTURA (PI)	8	1280
EMPAQUE (EQ)	6	960
DESPACHO (DP)	4	640

Tabla 5. Consumo de las actividades según el producto.

Actividad	X_1[h/u]	X_2[h/u]	X_3[h/u]	X_4[h/u]
DESCARGA (DC)	0,33	0,283	0,5	0,025
ALMACENAMIENTO (AL)	0,0167	0,025	0,005	0,04
ENSAMBLE(EN)	0,49	0,361	0,32	0,56
PINTURA (PI)	0,65	0,25	0,42	0,68
EMPAQUE (EQ)	0,65	0,68	0,74	0,62
DESPACHO (DP)	0,6	0,6	0,45	0,3

Finalmente, en Tabla 6, se presenta el análisis de la capacidad de la instalación en función de la demanda proyectada.

Tabla 6. Consumo de los recursos para la demanda proyectada.

Act.	X_1	X_2	X_3	X_4	h. nec	h. disp.	%utilización
DC	266,7	127,5	250,0	15,0	659,2	640,0	103,0
AL	13,3	11,3	2,5	24,0	51,1	160,0	31,9
EN	392,0	162,5	160,0	336,0	1050,5	1920,0	54,7
PI	520,0	112,5	210,0	408,0	1250,5	1280,0	97,7
EQ	520,0	306,0	370,0	372,0	1568,0	960,0	163,3
DP	480,0	270,0	225,0	180,0	1155,0	640,0	**180,5**

Se observa que los recursos DC, EQ Y DP se encuentran sobrecargados si se desea satisfacer la totalidad de la demanda. Es decir, que se está en presencia de un sistema de múltiples cuellos de botella. El requerimiento más crítico es el correspondiente a la actividad de DP.

3.2 Obtención de la mezcla óptima (de máximo beneficio)

A partir de los datos presentados, se aplica el modelo de Programación Lineal (PL), a efectos de obtener la mezcla que maximiza el beneficio, utilizándose el complemento Solver de Excel.

Los resultados obtenidos para PL son:

- La mezcla que optimiza el beneficio está formada por 27 unidades de X_1, 450 de X_2, 500 de X_3 y 429 de X_4.
- El beneficio alcanzado por la fabricación y venta de esta mezcla es de $ 1.144.412,5
- Los recursos EQ y DP son los que más se utilizan, y prácticamente se han agotado.
- El recurso DC emplea 397,55 h.

Estos resultados son observados por los distintos expertos involucrados en la decisión, tal como se detalla a continuación:

- El Experto I, del Departamento de Finanzas, si bien comprende la insuficiente capacidad de fabricación, observa que con esta mezcla se alcanza el 61% del beneficio total posible de alcanzar con la demanda requerida;
- El Experto II, del Departamento de Operaciones, sostiene que no es deseable que las operaciones cuello de botella queden con horas ociosas;
- El Experto III, del Departamento de Recursos Humanos, observa la operación DC tiene asignados 4 operarios, al igual que la operación DP. Las horas ocupadas de DC alcanzan un 62% mientras que las de DP son casi el 100%. Esto revela un desbalanceo en el contenido de trabajo entre ambas operaciones, que en principio y dada su especialización, son regidas por el mismo convenio laboral (reciben la misma paga). Esta situación puede generar un entorno de trabajo insatisfactorio que afecte incluso, a toda la organización.
- El Experto IV, del Departamento de Comercialización, observa que sería importante que demanda de X_1 y X_2 sea satisfecha en un 100% dada la importancia del cliente.

Considerando estas observaciones se aplica el Modelo de Programación por Metas Ponderadas (PMP).

3.3 Aplicación de Modelo de Programación por Metas Ponderadas

Considerando las observaciones de los expertos, se definen las siguientes metas:

1. maximizar el beneficio
2. maximizar el uso del recurso DC a efectos de disminuir el desbalanceo entre puestos de trabajo similares;
3. maximizar la explotación de los cuellos de botella EQ y DP dado que son los recursos que restringen el sistema
4. satisfacer la totalidad de la demanda de X_1 y X_2

En consecuencia, se plantean las siguientes restricciones meta (ver Ecuaciones 12 a 17):

Meta 1: obtención del máximo beneficio:

$$838{,}75\,\mathbf{X_1} + 885{,}875\,\mathbf{X_2} + 1080\,\mathbf{X_3} + 452{,}5\,\mathbf{X_4} + \mathbf{n_1} = 1.881.143{,}75 \quad (5)$$

Meta 2: maximizar el uso del recurso DC

$$0{,}33\,\mathbf{X_1} + 0{,}283\mathbf{X_2} + 0{,}5\,\mathbf{X_3} + 0{,}025\,\mathbf{X_4} + \mathbf{n_2} = 640 \quad (6)$$

Meta 3: maximizar el uso del recurso EQ y DP

$$0{,}65\,\mathbf{X_1} + 0{,}68\,\mathbf{X_2} + 0{,}74\,\mathbf{X_3} + 0{,}62\,\mathbf{X_4} + \mathbf{n_3} = 960 \quad (7)$$

$$0{,}6\,\mathbf{X_1} + 0{,}6\,\mathbf{X_2} + 0{,}45\,\mathbf{X_3} + 0{,}3\,\mathbf{X_4} + \mathbf{n_4} = 640 \quad (8)$$

Meta 4: fabricar toda la demanda de x_1 y x_2

$$\mathbf{X_1} + \mathbf{n_5} = 800 \quad (9)$$

$$\mathbf{X_2} + \mathbf{n_6} = 450 \quad (10)$$

Se proponen 2 modelos distintos. En el primer modelo, se analiza el resultado de no establecer preferencia alguna entre las metas a cumplir.

En el segundo modelo, se introducen las preferencias entre los distintos expertos, para cumplir con las metas.

PMP con metas normalizadas e igualmente ponderadas (PMN)

En este caso, el funcional responde a la siguiente expresión, Ecuación 18:

$$\text{Min } z = g(n_1, n_2, n_3, n_4, n_5, n_6) \quad (11)$$

- ✓ Las restricciones metas son las que se presentan en ecuaciones 12 a 17
- ✓ Las restricciones de capacidad del sistema, se muestran en las Ecuaciones 19 a 21:

$$\text{Hs AL} \quad 0{,}017\,X_1 + 0{,}025\,X_2 + 0{,}005\,X_3 + 0{,}04\,X_4 \leq 160 \quad (12)$$

$$\text{Hs EN} \quad 0{,}49X_1 + 0{,}361X_2 + 0{,}32X_3 + 0{,}56X_4 \leq 1920 \quad (13)$$

$$\text{Hs PI} \quad 0{,}65X_1 + 0{,}25X_2 + 0{,}42X_3 + 0{,}68X_4 \leq 1280 \quad (14)$$

$X_j \geq 0$ y entero

- ✓ Las restricciones de demanda, se visualizan en las Ecuaciones 22 y 23:

$$X_3 \leq 500 \quad (15)$$

$$X_4 \leq 600 \quad (16)$$

Los coeficientes de las desviaciones se normalizan, dividiendo los mismos por su función objetivo

Utilizando el complemento Solver de Excel, se obtienen los siguientes resultados para PMN:

- la mezcla está formada por 242 unidades de X_1, 449 de X_2, 500 de X_3 y 1 de X_4.
- El beneficio obtenido es de $ 1.141.187,88.
- El recurso DC utilizado 413,16h h.
- El recurso EP utilizado es de 959,63 h.
- El recurso DP utilizado es de 639,9 h.

Programación por Metas Ponderadas según criterio del decisor (PMAIJ)

Para la ponderación de los criterios se utiliza una matriz de comparaciones pareadas que permite al decisor determinar la importancia relativa de las desviaciones no deseadas. Se definen:

C_1: coeficiente que pondera el beneficio
C_2: coeficiente que pondera explotación de DC
C_3: coeficiente que pondera explotación de EQ
C_4: coeficiente que pondera explotación de DP
C_5: coeficiente que pondera las ventas de X_1

C_6: coeficiente que pondera las ventas de X_2

En las Tablas 7 a 10 se presentan las matrices de comparaciones pareadas arrojadas por los distintos expertos. Las ponderaciones se realizaron utilizando la escala de Saaty.

Tabla 7. Comparación pareada de los coeficientes Experto I.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	6	6	6	3	3
C_2	0,167	1	1	1	1	1
C_3	0,167	1	1	1	1	1
C_4	0,167	1	1	1	1	1
C_5	0,333	1	1	1	1	1
C_6	0.333	1	1	1	1	1

Tabla 8. Comparación **pareada de los coeficientes Experto II.**

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	0,111	1	1	1	1
C_2	9	1	7	7	6	6
C_3	1	0,143	1	1	1	1
C_4	1	0,143	1	1	1	1
C_5	1	0,167	1	1	1	1
C_6	1	0,167	1	1	1	1

Tabla 9. Comparación pareada de los coeficientes Experto III.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	1	0,143	0,143	1	1
C_2	1	1	0,143	0,143	1	1
C_3	7	7	1	1	5	5
C_4	7	7	1	1	5	5
C_5	1	1	0,2	0,2	1	1
C_6	1	1	0,2	0,2	1	1

Tabla 10. Comparación pareada de los coeficientes Experto IV.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	1	1	1	0,143	0,143
C_2	1	1	1	1	0,2	0,2
C_3	1	1	1	1	0,2	0,2
C_4	1	1	1	1	0,2	0,2
C_5	7	5	5	5	1	1
C_6	7	5	5	5	1	1

Las opiniones de los expertos se agregan en un juicio único, utilizando el enfoque AIJ. La Tabla 11 presenta la matriz agregada, utilizando media geométrica. La Tabla 12 la matriz agregada normalizada y el vector resultante. Los componentes de dicho vector representan los coeficientes de ponderación de las desviaciones.

Tabla 11. Matriz Agregada.

	C_1	C_2	C_3	C_4	C_5	C_6
C_1	1	0,904	0,962	0,962	0,809	0,809
C_2	1,107	1	1	1	1,047	1,047
C_3	1,04	1	1	1	1	1
C_4	1,04	1	1	1	1	1
C_5	1,236	0,955	1	1	1	1
C_6	1,236	0,955	1	1	1	1
SUMA	6,657	5,814	5,962	5,962	5,856	5,856

Tabla 12. Matriz normalizada y resultante.

	C_1	C_2	C_3	C_4	C_5	C_6	VECTOR
C_1	0,150	0,155	0,161	0,161	0,138	0,138	**0,151**
C_2	0,166	0,172	0,168	0,168	0,179	0,179	**0,172**
C_3	0,156	0,172	0,168	0,168	0,171	0,171	**0,168**
C_4	0,156	0,172	0,168	0,168	0,171	0,171	**0,168**
C_5	0,186	0,164	0,168	0,168	0,171	0,171	**0,171**
C_6	0,186	0,164	0,168	0,168	0,171	0,171	**0,171**

Se calcula RC = 0,00083 verificando de esta forma, la consistencia de la matriz.

Los componentes del vector resultante, se normalizan y se introducen en el modelo de PMP.

Utilizando el complemento Solver de Excel, y se obtienen los siguientes resultados para PMAIJ:

- la mezcla está formada por 616 unidades de X_1, 449 de X_2, 2 de X_3 y ninguna de X_4.
- El beneficio obtenido es de $ 916.587,88
- El recurso DC utilizado 333,55 h.
- El recurso EP utilizado es de 707,2 h.
- El recurso DP utilizado es de 639,9 h.

4 Análisis de resultados

En las Fig. 1 a 4 se observa cómo varían el beneficio total, las horas en DP, EQ, DP y la mezcla, en función del modelo utilizado:

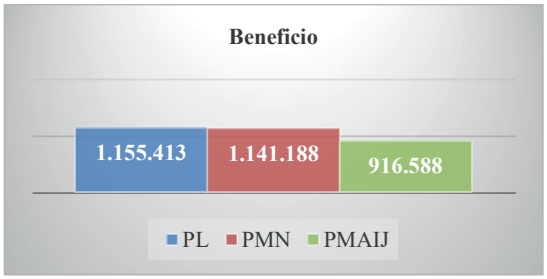

Fig. 1. Beneficio Total según modelo.

Este resultado indica que la mezcla de AIJ es la que arroja menor beneficio

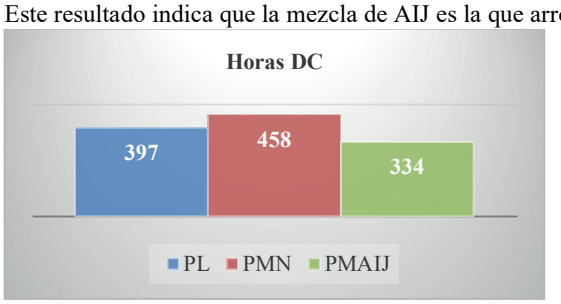

Fig. 2. Horas ocupadas en operación DC, Según modelo.

La PMN es la que más se acerca a la meta de máxima ocupación en DC

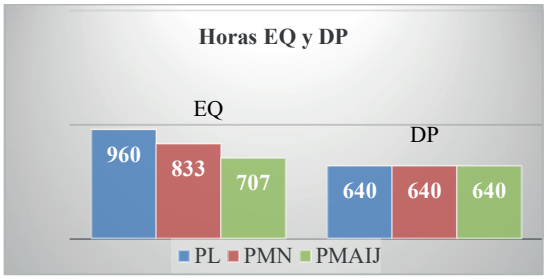

Fig. 3. Horas ocupadas en operaciones EQ y DP, según modelo.

Las horas ocupadas en DC, tanto de PMN como en PMAIJ son menores que las que arroja el modelo de PL.
Las horas ocupadas en DP no se ven afectadas por el modelo utilizado.

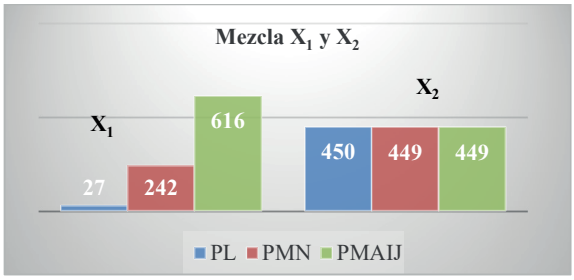

Fig. 4. Valor de mezcla para X_1 y X_2, según modelo.

Se observa que el valor de X_1 si bien no llega a la meta de 800, en PMN aumenta su valor respecto de PL y en PMAIJ alcanza el máximo valor alcanzado.

Respecto de X_2, se observa que la mezcla de PL es la que alcanza en forma rigurosa la meta buscada, aunque los modelos PMN y PMAIJ, prácticamente también lo hacen.

A modo de resumen de resultados, y considerando las metas planteadas, se puede afirmar que:

- El modelo de PL proporciona la mezcla que maximiza el beneficio;
- El efecto de considerar las metas igualmente ponderadas y normalizadas se observa que genera, un aumento de la utilización de horas de DC
- La máxima ocupación de EQ se obtiene para el modelo PL
- Las horas de ocupación de DP no se ven afectadas por la introducción de las metas en el modelo
- Finalmente, las mezcla que más ajusta a la meta 4 es el modelo de PMAIJ, que proporciona un 77% de la producción de X_1 y un 99,8% de la demanda de X_2, que es el mayor porcentaje alcanzado. Esta propuesta permite tomar la decisión de seleccionar el modelo de PMAIJ para la planificación de la producción.

Si bien es el modelo de menor rentabilidad, la metodología utilizada hace que esta decisión esté firmemente sustentada y en consecuencia de difícil objeción.

5 Conclusiones

El problema de obtención de la mezcla de producción en un entorno de múltiples cuellos de botella, se resuelve habitualmente utilizando la técnica de Programación Lineal.

No obstante, el empleo de este modelo, considera como único objetivo a tener en cuenta el beneficio.

La Programación por Metas en cambio, permite la consideración de otros objetivos que las partes interesadas puede suponer importantes en la determinación de la mezcla, confiriendo flexibilidad al modelo.

La Programación por Metas Ponderadas, además permite al decisor introducir su opinión respecto de la importancia de dichos factores. Dicha ponderación se puede realizar utilizando el Proceso Analítico de Jerarquías, de forma tal de no incurrir en inconsistencias al momento de emitir los juicios. El modelo AIJ permite incluir la opinión de todos los involucrados en la decisión.

La metodología propuesta de utilizar en forma conjunta el PAJ y la PMP en la determinación de la mezcla de producción en un entorno de múltiples objetivos resultó efectiva y de fácil aplicación, brindando resultados sólidamente sustentados.

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Customer order scheduling problem to minimize total tardiness with sequence-dependent setup times

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Abstract. In this work, we introduce the order scheduling problem, in which customer orders (composed of different individual tasks) are scheduled, where the objective function is the minimization of the total tardiness of completed orders. In the reviewed literature, less studies regarding the problem of sequencing of customer orders were found compared with other production environments, such as, parallel machines or flow shop. In this work, we present a new variant for that problem, where we explicitly consider the setup times of machines dependent on the production sequence, which belongs to the NP-hard class. Then, we propose a new formulation using linear integer programming, an adaptation of the OMDD heuristic (referred to as OMMD-S), and a matheuristic called Same Permutation in All Machines (SPAM). The extensive computational simulations carried out show that the SPAM matheuristic is the most efficient for the evaluated instances.

Keywords: Production Sequencing. Heuristic. Matheuristic. Combinatorial Optimization. Mixed-Integer Linear Programming.

1 Introduction

A set of n orders needs to be processed on a set of m dedicated parallel machines, where each machine can process only one type of operation. Each order has an associated setup time, which is sequence-dependent, as well as a due date, related to the customer requirements. The customer order scheduling problem has several industrial applications, such as the paper industry, the pharmaceutical industry, and assembly operations [16]. Thereby, this production environment has received a lot of attention from many researchers [4].

Here, we present the literature review taking into account the notation provided by Framinan et al. [4]. Wagneur and Sriskandarajar [17] approached an open shop scheduling environment where the overlap of jobs in the available machines is allowed. The NP-hardness of the variant, taking into account the total tardiness minimization ($DPm \rightarrow 0||\Sigma T$), has been proven. Leung et al. [9] presented a notation for order scheduling linear programming models, considering several conditions for a given production environment and several objective functions. Roemer [16] approached the concurrent open shop where the jobs are processed in dedicated parallel machines. Contrary

to the statement presented by Wagneur and Sriskandarajar [17], Roemer re-established that, even for two machines, the problem for average completion time is NP-hard in the strong sense.

Leung et al. [10] approach the customer order scheduling problems that may present release dates and due dates. The class of objective functions treated involves total completion time and total tardiness performance measures, and the weighted total completion time objective is focused. The above-mentioned authors presented several structural properties and complexity analyses. Besides, two constructive heuristics, as well as a tabu search metaheuristic, are proposed.

Framinan and Perez-Gonzalez [2] addressed the customer order scheduling for total completion time minimization. A constructive algorithm with a look-ahead mechanism was proposed, which was used as an initial solution for a Greedy Search Algorithm (GSA) metaheuristic. Riahi et al. [15] developed eight dispatch rules, and a constructive algorithm, that considered all possible positions in the partial sequence for unscheduled orders. This constructive heuristic is used in a Perturbative Search Algorithm (PSA) metaheuristic.

Leung et al. [11] considered customer order scheduling problems with due date related objectives. Several performance measures are approached, and two objectives were focused: the minimization of the maximum lateness, and the total number of late orders. As solution procedures, a constructive heuristic and an exact algorithm were proposed. Lee [8] addressed the $DPm \rightarrow 0||\Sigma T$, and proven that the optimal solution for the total tardiness minimization is composed by the same permutation in all machines. Also, a mixed-integer linear programming formulation is presented. Finally, four constructive heuristics, as well as a Branch-and-Bound (B&B) algorithm, are proposed. In this study, OMDD heuristic may be considered as the best approximate algorithm for the problem. Framinan and Perez-Gonzalez [3] extended the constructive heuristic previously proposed for the total completion time objective [2] and developed two matheuristics called JPF and JPO. The second one is the state-of-the-art algorithm for $DPm \rightarrow 0||\Sigma T$ variant.

Kung et al. [7] addressed a customer order scheduling environment with unequal order ready times for the total completion time minimization. Two lower bounds are developed, and some problem properties were explored. Eight metaheuristics were proposed to solve the problem: four simulated annealings (SA) algorithms, and four genetic algorithms (GAs). Also, a Branch-and-Bound (B&B) algorithm was presented. Computational results point out that SA-based algorithms outperformed the GAs. Lin et al. [12] addressed a customer order scheduling environment with release dates for the minimization of the weighted number of tardy orders. Some dominance properties were explored, and a lower bound was presented. Besides, a B&B algorithm is developed to determine global optimal solutions. As solution procedures, these authors presented four standard bee colony algorithms, followed by four hybrid bee colony algorithms for finding near-optimal solutions within acceptable computational times. Wu et al. [18] introduced a customer order scheduling variant with ready times. Several dominance rules were explored, and two lower bounds were developed. These elements were considered in the developed B&B algorithm. These authors adapted five existing

constructive heuristics to the problem under study and proposed an Iterated Greedy (IG) metaheuristic.

Prata et al. [14] introduced the order scheduling problem with sequence-dependent setup times. Two mixed-integer linear programming models are proposed for this variant. Besides, two matheuristics are developed, which reduce the number of decision variables. The proposed Fixed Variable List Algorithm (FVLA) outperforms all other approaches.

Based on the literature review, we can observe that the variant introduced here is not reported previously. In a recent literature survey, Framinan et al. [4] have not reported contributions to the customer order scheduling environment with explicit setup times. In this paper, we introduce the customer order scheduling problem with sequence-dependent setup times for the total tardiness minimization. We present a mixed-integer linear programming model, as well as explore some problem properties. As a solution procedure, we extend two existing constructive heuristics. Also, we present a matheuristic procedure based on the reduction of the number of decision variables. Finally, we carried out extensive computational experiments with random-generated test instances.

The rest of this paper is organized as follows. In Section 2, we describe the problem under study. In Section 3, we present the proposed solution approaches. In Section 4, we summarize the computational results. Finally, in Section 5, we present the final remarks as well as suggestions for future works.

2 Problem description

2.1 NP-hardness of the proposed variant

Wagneur and Sriskandarajah [17] proven the NP-hardness of the problem $DPm \rightarrow 0||\sum T_j$. In the problem under study ($DPm \rightarrow 0|ST_{SD}|\sum T_j$), we consider explicitally sequence-dependent setup times for each customer order. Thereby, the problem under study is also NP-hard since it can be reduced to the $DPm \rightarrow 0||\sum T_j$ if $S_{ikl} = 0, \forall i,k,l$.

2.2 Proposed MILP formulation

Since the proposed variant is NP-hard, there is no exact algorithm to solve the problem within polynomial time. Thereby, a mixed-integer linear programming formulation can obtain near-optimal solutions or even global optimal solutions to the problem under study. Let n be the number of orders to be produced in a set of m dedicated parallel machines. Each order k has an associated due date d_k, a processing time p_{ik} in machine i, and a sequence-dependent S_{ilk}. The problem is to find a sequence of orders where the total tardiness is minimized. Next, we define the tardiness for a given order, as well as the total tardiness minimization.

The completion time in machine i for a given order processed in postion j of sequence Π, $C_{i,\pi_j}(\Pi)$, can be calculated recursivelly as in Equation (1):

$$C_{i,\pi_j}(\Pi) = C_{i,\pi_{j-1}}(\Pi) + p_{i,\pi_j} + S_{i,\pi_{j-1},\pi_j}, \quad i = 1,\ldots,m, \quad j = 1,\ldots,n, \qquad (1)$$

with $C_{i,\pi_0}(\Pi) := 0$, $\forall i$. Therefore, $C_{\pi_j}(\Pi)$ the completion time scheduled in position j is defined as in Equation (2):

$$C_{\pi_j}(\Pi) = \max_{1 \leq i \leq m} \{C_{i,\pi_j}(\Pi)\}. \tag{2}$$

Analogously, the tardiness of order scheduled in position j can be defined as in Equation (3):

$$T_{\pi_j}(\Pi) = \max\{C_{\pi_j}(\Pi) - d_{\pi_j}; 0\}. \tag{3}$$

Finally, the total tardiness is calculated as $T(\Pi) = \sum_{j=1}^{n} T_{\pi_j}(\Pi)$.

Likewise, the summation of the completion times $C(\Pi)$ for a given sequence Π can be calculated as $C(\Pi) = \sum_{j=1}^{n} C_{\pi_j}(\Pi)$.

We extend the MILP model presented by Framinan and Perez-Gonzalez [3], taking into account different permutations in the available machines. The problem notation is presented as follows.

Indices and sets

Set of machines $I = \{1, \ldots, m\}$;
Set of orders $K = \{1, \ldots, n\}$;
Set of positions $J = \{1, \ldots, n\}$.

Parameters

p_{ik} : processing time of the order k in machine i;
S_{ijk} : setup time of the order k in position j of machine i.
d_k : due date of the order k;
M : a sufficiently large number.

Decision variables

T_k : tardiness of order k;
C_{ij} : completion time of position j in machine i;
D_{ij}: setup time of position j in machine i.

$$x_{ijk} = \begin{cases} 1, & \text{if the order } k \text{ is processed in the position } j \text{ of machine } i. \\ 0, & \text{otherwise} \end{cases}$$

The MILP model is presented as follows:

$$\min \sum_{k=1}^{n} T_k \tag{4}$$

$$\text{subject to:} \quad \sum_{k=1}^{n} x_{ijk} = 1, \quad \forall i \in I, \quad \forall j \in J \tag{5}$$

$$\sum_{j=1}^{n} x_{ijk} = 1, \quad \forall i \in I, \quad \forall k \in K \tag{6}$$

$$S_{ijk}(x_{ij-1k} + x_{ijl} - 1) \leq D_{ij}, \quad \forall i \in I, \quad \forall j > 1, \quad \forall k,l \in K \tag{7}$$

$$\sum_{r=1}^{j} D_{ir} + \sum_{k=1}^{n} \sum_{r=1}^{j} p_{ik} \cdot x_{irk} \leq C_{ij}, \quad \forall i \in I, \quad \forall j \in J \tag{8}$$

$$C_{ij} - d_k + x_{ijk} \cdot M \leq M + T_k \quad \forall i \in I, \forall j \in J, \forall k \in K \tag{9}$$

$$x_{ijk} \in \{0,1\}, \quad T_k \geq 0, \quad C_{ij} \geq 0, \quad D_{ij} \geq 0, \quad \forall i \in I, \quad \forall k \in K, \quad \forall j \in J \tag{10}$$

The objective function (4) is the total tardiness minimization. Constraints (5) ensure that an order is scheduled only in one position of machine i. Set of constraints (6) enforces that a position is occupied only by a job from the order k in machine i. Set of constraints (7) calculates de setup time of the machine i in position j. We assume that all the machines are prepared in the first postion (the setups times are only computed if j is greater than 1). Set of constraints (8) computes the completion times of the orders. Constraint set (9) determines the tardiness associated with each customer order. Finally, constraint sets (10) establish the domain of the decision variables.

We define the M value as the summation of the processing and setup times, as in Equation (11):

$$M = \sum_{i=1}^{m} \sum_{k=1}^{n} p_{ik} + \sum_{i=1}^{m} \sum_{k=1}^{n} \sum_{l=1}^{n} S_{ikl} \tag{11}$$

Finally, it should be noticed that for this problem we have to consider the possibility of different permutations for every machine. Contrary to the variant without sequence-dependent setup times, where the optimal solution is obtained applying the same permutation on all the available machines [8]. Here, we show a counter-example to this fact.

Taking into account the following example, as described in Table 1. Also, we consider a due date of 5 time units for both orders.

Using the same permutation in all machines, we obtain the results illustrated in Figure 1, which present a total tardiness of the 4 and 8 time units, respectivelly. If we use distinct permutations in the machines, we can obtain a total tardiness of 3 time units, as illustrated in Figure 2. Thus, solutions with distinct permutations in the machines can lead to smaller total tardiness than solutions with fixed permutations in the machines.

Processing times		
	O_1	O_2
M_1	2	1
M_2	3	4

Setup times - machine 1		
	O_1	O_2
O_1	-	1
O_2	10	-

Setup times - machine 2		
	O_1	O_2
O_1	-	2
O_2	1	-

Table 1. Illustrative example.

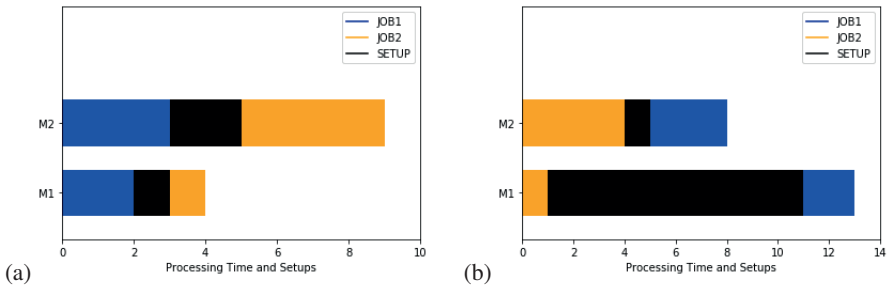

Fig. 1. Solutions with fixed permutations.

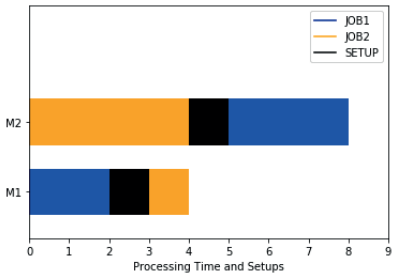

Fig. 2. Solution with distinct permutations.

3 Proposed solution approaches

Since the proposed variant is a NP-hard problem, we presented heuristic algorithms to find high-quality solutions within admissible computational time.

3.1 Constructive heuristics

The OMDD-S heuristic is an extension of the OMDD proposed by Lee [8], taking into consideration the sequence-dependent setup times. Our proposal is described in the following steps.

- Step 0: Set $\Omega := (1,2,\ldots,n)$ (unscheduled orders), $\Pi := \emptyset$ (scheduled orders) and $t_i = 0\ (1 \leq i \leq m)$.
- Step 1: Select order r in Ω with the minimum value of index α_j:

$$\alpha_j = \max\left\{\max_{1\leq i\leq m}\{t_i + S_{irj} + p_{ij}\} - \max_{1\leq i\leq m}\{t_i\}; d_j - \max_{1\leq i\leq m}\{t_i\}\right\}. \qquad (12)$$

- Step 2: Remove order r from Ω, append it at the end of Π.
- Step 3: Update t_i. If $|\Omega| = n-1$, then $t_i := t_i + p_{ir}$; otherwise, $t_i := t_i + S_{iwr} + p_{ir}$, where w is the last but one elemetn from Π.
- Step 4: While Ω is not empty, return to Step 1.

Also, we present the FP-S heuristic, as an extension of the FP algorithm proposed by Framinan and Perez-Gonzalez [3], taking into account the sequence-dependent setup times. The above-mentioned algorithm builds a solution $\Pi := (\pi_1, \ldots, \pi_n)$ from a set of unscheduled orders $\mathscr{U}$. Initially, $\mathscr{U}$ has all the orders, since none of the orders was scheduled. In iteration $\mathscr{K}$, each order in $\mathscr{U}$ is selected as a candidate to be inserted in the last position of Π. Aiming to select a given order from the candidate list, for each order $\omega_l \in \mathscr{U}$ with a due date d_l, a partial sequence S_l is builded inserting ω_l in the last position of Π, i.e. $\Pi := (\pi_1, \ldots, \pi_{k-1}, \omega_l)$.

Therefore, the tardiness indicator η_l for the candidate l is calculated as in Equation (13):

$$\eta_l = \max\{C(S_l) - d_l; 0\} + T^*(S_l) \tag{13}$$

where the first term is the contribution to the total tardiness if ω_l is selected, in which $C(S_l)$ is the completion time of the partial sequence S_l and d_l is the associated due date. The second term $T^*(S_l)$ estimates the contribution to the total tardiness of the remainder unscheduled orders. Figure 3.1 illustrates the FP-S constructive heuristic.

We adopt Ω as a given sequence where all the orders are included before the iterative procedure. For each iteration, we calculate $T^*(S_l)$ considering the remaining orders are scheduled after the orders in Π. We consider the sequence returned by the Earliest Due Date (EDD) heuristic. This algorithm is a well-known priority rule to solve a scheduling problem with due dates [13]. We select a given order, append it at the end of the partial sequence, and remove it from Ω. As the remaining orders in Ω are already sorted, they are not calculated again in the next iteration.

3.2 Matheuristic

An intuitive procedure to solve the problem under study is to consider a fixed permutation in all machines. In this way, we can replace the decision variable x_{ijk} in the model defined in Equations (4) - (10) by a decision variable x_{kj} equals to 1 if the order k is processed in position j, 0 otherwise. This matheuristic called Same Permutation in All Machines (SPAM) reduces the number of binary decision variables from mn^2 to n^2. We can observe that the optimal solution returned by the SPAM matheuristic not necessarily is the optimal solution to the original problem.

4 Computational results

4.1 Experimental design

Since the problem under study was not reported yet, we randomly generated the evaluated test instances, based on the related instances previously presented [8,3]. The

Algoritmo: FP-S

Input : Number of machines m, number of orders n, processing time p, due dates d, setup times s.
Output : Permutation Π
$\Pi := \emptyset$;
Obtain sequence $\Omega := (\omega_l, \ldots, \omega_n)$ by sorting orders according to EDD rule;
Set $ct_i = 0$ $(1 \leq i \leq m)$;
//Append orders one by one
for $j = 1$ *to* n **do**
  //Compute indicator for each unscheduled order
  for each $\omega_l \in \Omega$ **do**
    //Compute ect_i the estimated completion times of ω_l for each machine i;
    for $i = 1$ *to* m **do**
      $ect_i = ct_i + p_{iw_l} + s_{ilw_k}$
    end
    Where l is the last element of Π
    //Compute first term of indicator η_l, see Equation 13
    $\eta_l = \max\{\max_{1 \leq i \leq m}\{ect_i\} - d_{w_l}; 0\}$
    //Compute second term of indicator η_l
    for each $w_k \in \Omega - \{w_t\}$ **do**
      for $i = 1$ *to* m **do**
        $ect_i = ect_i + p_{iw_k} + s_{ilw_k}$
      end
      $\eta_l = \eta_l + \max\{\max_{1 \leq i \leq m}\{ect_i\} - d_{w_k}; 0\}$
    end
  end
  //Select order with minimum value of η_l
  $r := argmin_{1 \leq l \leq n-j+1} \eta_l$
  Append ω_l at the end Π, i.e. $\Pi := (\pi_1, \ldots, \pi_{j-1}, \omega_r)$
  Extract ω_r from Ω, i.e. $\Omega := (\omega_l, \ldots, \omega_{r-1}, \omega_{r+1}, \ldots, \omega_{n-j+1})$
  //Update completion times
  for $i = 1$ *to* m **do**
    $ct_i = ct_i + p_{iw_r} + s_{ilw_r}$
  end
end

Fig. 3. Pseudocode of FP-S constructive heuristic.

testbed is composed of test instances with $n \in \{10, 20, 30, 40\}$ and $m \in \{2, 5, 8\}$. The processing times follow an uniform distribution $U[1, 100]$. The sequence-dependent setup times follow three uniform distributions $\{U[1, 25], U[26, 75], U[76, 125]\}$. The due date d_k follows a uniform distribution $U[P(1 - TF - RDD/2), P(1 - TF + RDD/2)]$, where:

– P is the sum of processing and setup times divided by the number of machines. Aiming to generate tight due dates, we multiply this expression by a factor μ.

$$P = \left\lceil \frac{\sum_{i=1}^{m}\sum_{k=1}^{n} p_{ik} + \sum_{i=1}^{m}\sum_{k=1}^{n}\sum_{l=1}^{n} S_{ikl}}{m} \right\rceil \cdot \mu,$$

- *RDD* is the interval for due dates: $RDD : \{0.2, 0.5, 0.8\}$;
- *TF* is the tardiness factor for the due dates: $TF : \{0.2, 0.5, 0.8\}$

For each combination of parameters were generated 10 test instances, totalizing 3240 instances. The methods under comparison are listed below.

- EDD heuristic. ;
- OMDD heuristic [8];
- FP heuristic [3];
- The proposed OMDD-S heuristic;
- The proposed FP-S heuristic;
- The proposed SPAM matheuristic;
- The proposed MILP model.

We used the Relative Deviation Index (*RDI*) indicator as a performance measure, which is a standard indicator for scheduling problems with due-date objectives [6,1,5]. Let H be a set of methods, the *RDI* obtained for the method $s \in H$ when applied to instance t is calculated as in Equation (14).

$$RDI_{st} = \begin{cases} 0, \text{ if } \min_{h\in H} T_{ht} = \max_{h\in H} T_{ht}, \\ \frac{T_{st} - \min_{h\in H} T_{ht}}{\max_{h\in H} T_{ht} - \min_{h\in H} T_{ht}} \cdot 100, \quad \text{otherwise.} \end{cases} \tag{14}$$

where T_{st} is the tardiness value obtained by heuristic s in instance t. In our case $\min_{h\in H} T_{ht}$ is the optimal value if the MILP model is able to find the optimal solution within the assigned computation time, or the best solution found among the heuristics and matheuristics otherwise. The methods under comparison were implemented with Python 3.7. Furthermore, the MILP model and the SPAM matheuristic were solved with IBM ILOG CPLEX version 12.8.0. For all methods under comparison, we adopt a time limit t_{limit} = 600s. All the algorithms were run in an Intel Core i5-3470 with 3.20 GHz and 8 GB RAM.

4.2 Results and discussion

Table 2 illustrates the computational results for different values of m and n. Taking into consideration the first set of instances ($m = 2$ and $n = 10$), we can observe that the MILP model returns the best solutions among all the considered methods. However, with the increasing of the values of m and n, OMDD-S and SPAM return the best *RDI* values.

Based on Table 2, we can observe that FP-S algorithm outperforms the FP heuristics since the first one presents smaller average *RDI* values for all the sets of instances, except for the problems with $m = 8$ and $n = 40$. However, the difference between the

RDI values between FP-S and FP heuristics in these test instances is only 0.0363%. We can also emphisize that OMDD-S algorithm outperforms the OMDD heuristic since it returned best average *RDI* values for all the test instances. Furthermore, OMDD-S presented the better results taking into account all the methods under comparison for the test instances with $m = 2$ and $n = 40$, $m = 5$ and $n = 30$, $m = 5$ and $n = 40$, $m = 8$ and $n = 30$, and $m = 8$ and $n = 40$.

Table 2. *RDI* values for m and n.

m	n	EDD		FP		FP-S		OMDD		OMDD-S		SPAM		MILP	
		Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.
2	10	96.0493	9.3616	74.0338	25.0662	56.2146	27.9379	71.7094	26.1252	38.9890	21.3437	4.0962	6.0115	**2.5621**	5.0161
	20	78.0802	39.7039	59.6758	36.7352	50.7040	35.8896	60.4745	37.3009	34.3478	28.6449	**1.3400**	3.7905	9.3785	12.9342
	30	51.2699	47.9732	38.7799	38.8774	32.3618	34.8804	37.3278	38.5403	14.9357	21.4638	**3.2868**	11.3513	29.6013	35.5334
	40	30.6066	41.6651	20.6749	29.2184	16.1128	24.1090	20.6244	29.4594	**5.3353**	12.1637	7.2014	16.0259	47.7702	46.3508
5	10	93.7856	12.8498	73.2224	23.6788	58.8051	26.2510	67.0564	26.0498	37.3649	21.3112	**0.7320**	3.5071	44.3834	31.3414
	20	68.5931	38.5886	51.8753	33.9332	47.7414	33.6977	49.3869	34.2624	26.2016	27.6356	**1.5034**	5.5553	56.6971	40.8459
	30	24.7276	29.9120	15.6652	19.8134	14.0038	19.0648	14.6226	19.5513	**4.8897**	13.0445	7.9156	18.7946	63.7574	47.0489
	40	12.5207	18.9695	7.7062	11.2894	6.2386	8.9795	7.2035	12.0241	**0.7864**	3.8819	13.7649	23.4343	63.6526	48.1386
8	10	91.4871	15.5632	68.0999	24.8717	56.2083	25.4117	64.4250	26.7497	34.7448	20.1781	**0.3887**	2.6978	59.7256	29.8778
	20	47.8521	34.6717	35.4197	30.6066	32.0334	30.9338	34.0509	30.4694	16.3356	24.0658	**2.1620**	6.2871	72.9362	42.2317
	30	13.7397	16.9201	8.3019	9.1562	7.5901	9.4229	7.1592	8.7618	**1.1804**	3.0884	8.6284	15.6743	70.3357	45.7281
	40	7.0810	10.0842	4.0630	5.4360	4.0993	5.6086	3.7153	5.1559	**0.0747**	0.4838	16.1054	24.7717	65.4765	47.5565
Total		51.3161	43.6518	38.1265	36.6097	31.8428	32.8324	36.4797	36.2311	17.9322	24.0582	**5.5937**	14.6616	48.8564	44.5224

Table 3 presents the *RDI* values (average and standard deviation) taking into account *TF* and *RDD*. Once again, SPAM and OMDD-S have returned the best values for the RDI indicator. Also, the FP heuristic has presented the worst performance among the methods under comparison.

Taking into consideration the Table 3, we can observe that FP-S algorithm outperforms the FP heuristic for all the evaluated test instances. In addition, the OMDD-S algorithm outperforms the OMMD heuristics also for all the test instances. Finally, we can highlight that the SPAM matheuristic presented better average *RDI* values than the MILP model for all the available test instances.

Table 3. *RDI* values for TF and *RDD*.

TF	RDD	EDD		FP		FP-S		OMDD		OMDD-S		SPAM		MILP	
		Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.	Average	St. Dv.
0.2	0.2	49.6773	46.3111	37.8822	39.5605	32.2817	35.8777	38.9762	39.8445	24.7103	28.6539	**2.4181**	7.2048	21.9678	35.8238
	0.5	44.1905	45.6202	35.7829	39.8318	33.2857	37.9581	35.1393	39.3478	21.4946	29.2083	**3.8455**	12.3581	25.2510	38.6798
	0.8	35.8707	44.9105	27.9736	37.6936	24.3368	34.2221	26.1867	36.6468	14.3961	23.6771	**5.5174**	17.8131	26.1323	40.3943
0.5	0.2	60.6846	42.2314	46.3787	38.2754	39.7998	35.5474	46.2399	37.7658	26.2242	26.4104	**1.6616**	7.6374	39.4062	41.5167
	0.5	52.1371	44.0711	39.5297	37.8891	34.8908	35.7323	37.6649	37.8340	19.9293	26.1946	**2.9192**	11.2144	45.1481	44.4619
	0.8	45.3009	44.6112	32.6849	35.6797	26.9598	31.5178	31.9980	36.0993	15.0814	22.7089	**5.8147**	16.5870	58.6621	44.3116
0.8	0.2	64.1548	36.8234	44.6951	30.9881	34.4572	25.7447	41.7105	30.7024	14.4790	17.2662	**7.7060**	15.4199	71.9201	36.8675
	0.5	57.2449	38.8950	40.3117	31.0855	30.9332	25.4539	36.5306	30.6018	12.8570	16.5625	**9.9410**	16.8242	75.3578	35.5601
	0.8	52.5838	41.7645	37.8996	34.0979	29.6401	28.5309	33.8709	32.5434	12.2177	17.1035	**10.5200**	18.8095	75.8623	34.8575
Total		51.3161	43.6518	38.1265	36.6097	31.8428	32.8324	36.4797	36.2311	17.9322	24.0582	**5.5937**	14.6616	48.8564	44.5224

Figure 4 illustrates the boxplot for average *RDI* values taking into consideration the parameter TF. Based on achieved results, we can observe that SPAM matheuristic returned the best results for all the values of TF. Besides, the MILP model presented the worse results for TF equals to 0.8. Figure 5 illustrates the average *RDI* values depend-

ing on *RDD*. Once again, the SPAM matheuritic outperformed all the other methods under comparison.

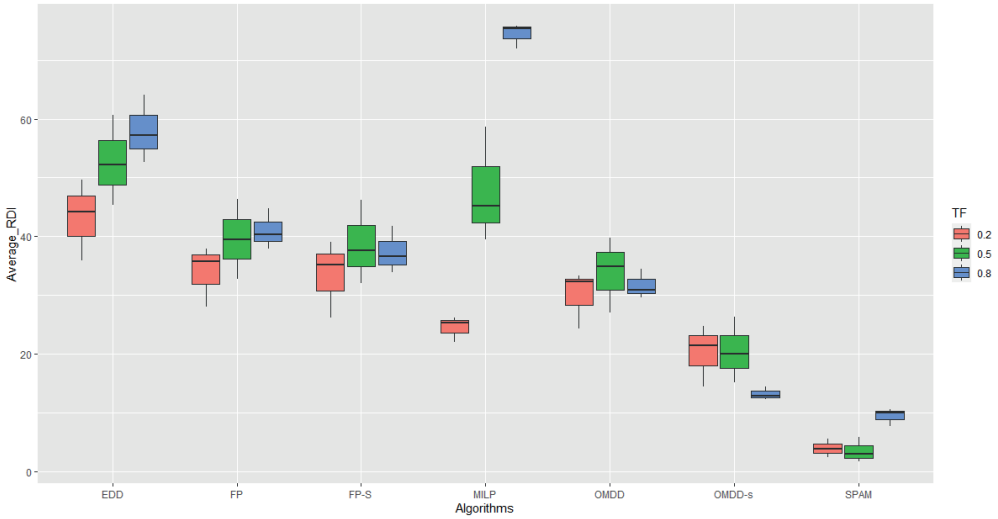

Fig. 4. Boxplot for average *RDI* values depending on TF.

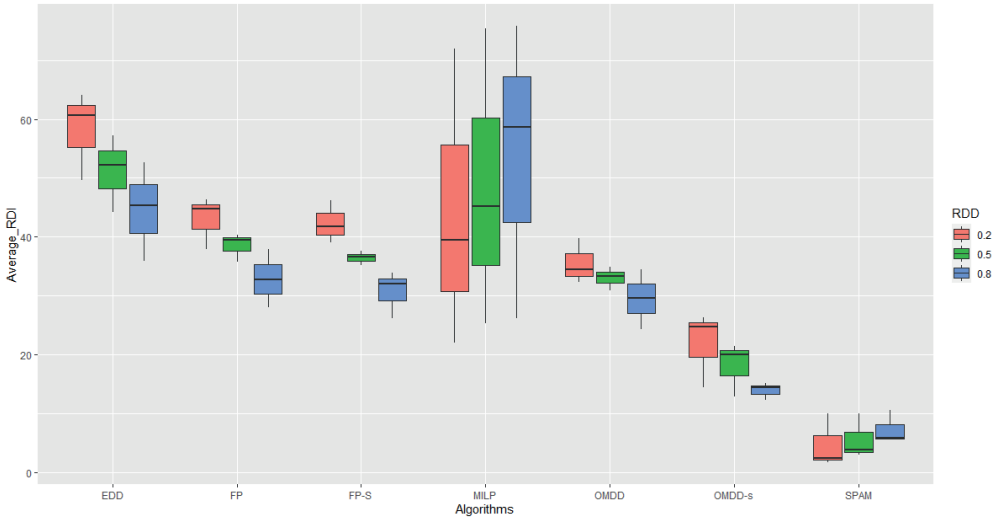

Fig. 5. Boxplot for average *RDI* values depending on *RDD*.

5 Conclusions

In this paper, a new variant for the customer order scheduling problem has been investigated, taking into consideration explicitly sequence-dependent setup times. The objective function is the total tardiness minimization. A mixed-integer linear programming formulation has been proposed for the problem under study. Furthermore, two constructive heuristics as well as a matheuristic based on the decision variable fixations have also been presented. The proposed matheuristic is a promising method to solve the problem under study since it outperformed all the other methods under comparison.

As extensions of this work, other matheuristics and matheuristics could be developed to improve the solutions found. The OMDD-S heuristic could be used as a warm start to MILP and SPAM methods, improving the solutions returned by these methods. Another possibility is the consideration of different objective functions for the proposed variant, such as total completion time.

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A Research Direction in Manufacturing Systems Scheduling: A proposal*

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Abstract. Manufacturing is the most important wealth-generating sector of a developed nation. However, this very important economic sector is facing intense global competitions. To be successful in this competitive climate, manufacturers require significantly improved capabilities. Technology, in the form of equipment and automation, has always been a means to competitiveness. However, an equally important and a determining avenue to competitiveness is the way we organize facilities, plan production and schedule operations. Production planning and scheduling has become a necessity for survival and its importance cannot be overstated. It is a critical decision making process of allocating limited resources to tasks over time, while many time and relationship constraints among the activities and resources are being satisfied. Indeed, it ultimately determines the operational performance of a manufacturing system. It is also one of the very difficult optimization problems known to the research community and has been an active field of research for many decades. Countless number of articles are published in the area. However, very little has been written on how to bring theoretical research into practice. Perhaps the research community has over emphasized the mathematical rigor at the cost of under-emphasizing real implementations. In this article, we discuss how to make scheduling research relevant in a form of new research directions.

Keywords: Manufacturing Systems Scheduling; Empirical Study; Meta-Scheduling; Dynamic Scheduling; Supervisory Control.

1 Introduction

Production scheduling has become a necessity for the survival of manufacturing firms in today's competitive marketplace (Kostas et al., 2003). It is a critical decision making process of allocating limited resources to tasks over time in or-der to produce the desired outputs at the desired time. Indeed, it ultimately determines the operational performance of a manufacturing system (Wiers and Tjerk W. Van Der Schaaf, 1997). Production scheduling usually involves a very

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large number of variables and constraints and it is one of the very difficult combinatorial optimization problems known to the research community. To this end, it becomes an active field in operations research and countless number of arti-cles are published in the area. However, most published articles are focused in developing models and algorithms for theoretical scheduling problems having well-defined structures such as job shop, flow shop, parallel machine shop and their variants. Whereas, scheduling in practice, varies greatly between different companies with no definitive model of "real world" scheduling available to aid manufacturing industries. Very little has been written on how to bring theoretical research into practice. This has given rise to the so-called "gap" between theory and practice of scheduling (MacCarthy and Liu, 1993). For instance, in a quantitative study about scheduling research carried out by Reisman and Kumar (1997), from a total of 184 reviewed papers, only 5 (less than a 3%) dealt with realistic production settings. Indeed, several other studies on production planning and scheduling have also concluded that there exists a gap between theory and practice (e.g. McKay and Wiers (1999), Wiers and Tjerk W. Van Der Schaaf (1997), Portougal and Robb (2000), Kostas et al. (2001), Gupta (2002), Mon-tana (2002), Méndez et al. (2006), Proth (2007), Framinan and Ruiz (2010), Jahangirian et al. (2010), De Snoo et al. (2011), Frantzén and Moore (2011), Framinan and Ruiz (2012), Carvalho et al. (2014)).

Sample statements in literature about the apparently perceived gap between theory and practice in scheduling are listed below:

- The academic literature presents a lack of studies examining the implementation of production scheduling solutions in real contexts (Carvalho et al., 2014).
- Advances in scheduling theory have had only a limited impact in practice (Pinedo, 2008).
- Research in scheduling has been motivated by what the researchers can achieve rather than what is important and suffers from much abstractions and too little application (Gupta and Edward, 2006).
- While advances in scheduling theory had become broader and covered more areas, industrial executives felt that the realistic scheduling problems were not being solved (Gupta, 2002).
- A big proportion of the theoretical research in scheduling done during the decades past is of limited use in real-world applications (Kostas et al., 2001).
- A proliferation of scheduling research has done little to improve production planning practice, despite calls for more comprehensive model (Portougal and Robb, 2000).
- Production scheduling in industrial practice is still primarily a manual task, despite immense research efforts and the fact that manual scheduling is a very complex task (Wiers and Tjerk W. Van Der Schaaf, 1997).

From the above review and other literature, it is apparent that there is consensus in the research community that theoretical research in developing algorithms for scheduling has done little to improve the scheduling practice. Perhaps the operations research community has over-emphasized the rigor in

mathematical treatment at the cost of under-emphasizing real implementations. Most scheduling tasks that could potentially benefit from automated scheduling are performed manually, that produces highly suboptimal schedules (Montana, 2002). The majority, if not all, of the contemporary enterprise resource planning (ERP) software do not support the production scheduling function (Kostas et al., 2003). In addition to those literature assertions, after conducting scheduling research in the past seven years and having seen several real life industrial problems, the author strongly believes that the countless scheduling algorithms appeared in literature have very limited use in practical settings. Thus, a scheduling research that better address the needs of the real world manufacturing industries is of a paramount importance which is the main driving force of the research proposal presented in this paper.

2 Proposal for Research Directions

2.1 Empirical Study

Real-world scheduling problems are extremely different from conventional research problems and quite often they are very complicated. One problem encountered by the author of this article in a local industry (with no resemblance to any scheduling problem in literature) involves a highly paced upstream continues process of a constant speed feeding hundreds of intermittent downstream operations interconnected by a network of conveyors. The scheduling of the downstream operations calls for a balance of material flows at each processing station and meeting production demands within posted time-windows. Another real-life scheduling problem, yet totally different from theoretical problem, encountered by the author involves the scheduling of parallel workstations feeding many different parts to a loop conveyor. Part carriers for different products are mounted on the conveyor on which parts are further processed. The carriers/fixtures for the different products have be added or removed from the conveyor to meet production schedules. The loading/unloading and the sequencing of the part-carriers on the conveyor and the operation of the parallel stations have to be synchronized to avoid starvation or congestion of the system and at the same time meet very tight production schedule. The above two encounters are just the tip of the iceberg. Industries are full of scheduling problems that are quite different from theoretical problems. Thus, for realistic problem formulations, an in-depth empirical study on the practice of manufacturing scheduling is much needed. In conducting empirical studies, researchers are advised to closely examine real life problems in industries and conduct extensive surveys. Using the results of such empirical study, it can be possible to develop generalized frameworks and guidelines for manufacturing systems scheduling that are usable in wide variety of practical scenarios.

2.2 Meta-Scheduling Procedure

A major problem in translating scheduling algorithms to real systems is that most algorithms are framework specific such as job-shop or flow-shop which

rarely match real systems Plenert and Kirchmier (2001), Mejía et al. (2012). In this research direction, researches are encouraged to develop a generalized framework and algorithm (meta-scheduling) that can be used to schedule a wide range of discrete manufacturing systems without altering its internal code. The manufacturing systems that can be scheduled with such algorithm can be a single machine shop, parallel machines shop, flexible flow shop, flexible job shop, cellular, virtual cellular, distributed, or hybrids of these layouts. Based on this framework, a meta-data structure, a meta-model and efficient solution procedure can be developed that can solve many of the discrete manufacturing systems scheduling problems appeared in literature. Such system independent generalized meta-scheduling algorithm can be more usable in practical settings as it will enable manufacturing system scheduler use the same scheduling tool in a variety of scenarios. This will also enable ERP tool developers to incorporate scheduling function as the algorithm can be coded without a specific system in mind and can handle a variety of scenarios without changing its coding.

2.3 Scheduling with Multiple Performance Metrics

The vast majority of scheduling algorithms in literature consider a single objective function (usually makespan). Whereas, the multi-objective ones added only one or two from the very limited list of other performance metrics such as earliness, lateness and tardiness that are well stabilised in scheduling research. Other performance measures, such as work-in-process inventory, machine utilization, and work-load balancing are not usually considered in scheduling while these performance metrics are ultimately impacted by scheduling. To address this issue, the meta-scheduling framework, highlighted in the previous section, has to be designed to be flexible enough to handle multiple objective functions and a variety of operational logics and constraints in manufacturing systems.

2.4 Integrated Dynamic Scheduling/Supervisory Control

Another major limitation of scheduling algorithms in literature is that most of them are designed assuming static conditions. However, manufacturing systems operate in dynamic environments where frequent real-time events occur making a previously feasible schedule obsolete. Examples of such real-time events include machine failures, arrival of urgent jobs, cancellation of orders, due date changes, operator absentee etc. To address this problem, algorithms need to be designed in such a way that they can be executed on (1) a fast simulated time to perform planning and scheduling, and (2) on a real time to perform supervisory control and automatic updates on the production schedule. In literature and in practice as well, supervisory control and scheduling are separate functions. Whereas, in this research direction, an integrated approach has to be pursued.

3 Suggested Methodology

The framework and the solution methodology to be develop is a hybrid approach combining metaheuristic algorithms (such as genetic algorithms) and Event-Scheduling/Time-Advance algorithm from the theory of discrete event systems simulation. This framework is depicted in Figure 1. The "Job Release Queue" is a set of alternative job dispatching sequences, to be iteratively improved and supplied by the metaheuristic algorithm. The schedule generator (the central part in Figure 1) works following the Time-Advance-Event-Scheduling algorithm as described in details in Figure 2. In that figure, a job in queue in front of a particular machine (resource) m is identified as (o, j, t_{ojm}) which represent operation o of job j and its future completion time t_{ojm}. The corresponding future job completion event is listed in a calendar as (o, j, m, t_{ojm}) in which all other job completion events are listed in chronological order. The schedule generator (running in a simulated time) provides schedules and performance measure for each potential job-release-sequence. Then, genetic operators are applied to provide a new set of job-release-sequences for the next iteration. The iteration continues until a predefined stopping criterion is met. The following paragraph briefly elaborates how this algorithm can be expanded to become a system independent multi-objective meta-scheduling tool by incorporating many pragmatic issues.

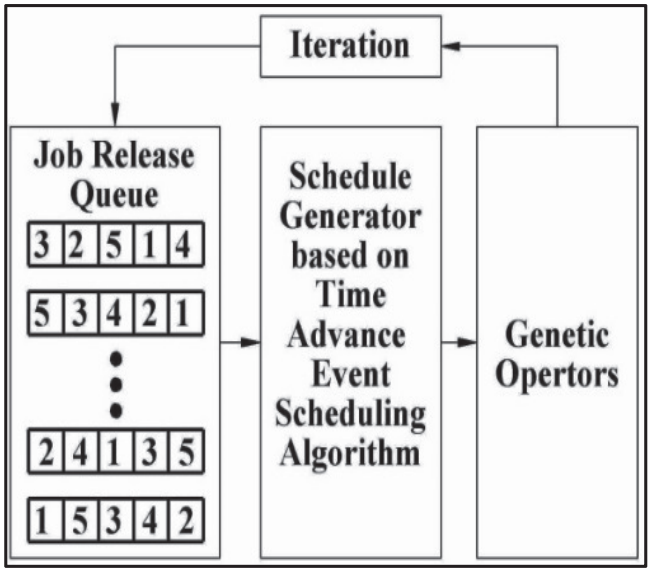

Fig. 1: The framework of the proposed methodology

As it can be seen in Figures 1 and 2, the algorithm does not require the type of machine layout adopted in the system as an input. Moreover, a resource m in the

schedule generator can be defined either as a unit processing (e.g. lathe, milling), a batch processing (e.g. heat treatment) or a continuous processing (e.g. painting line) or a material handling resource or even as buffer storage. As such, the algorithm can be expanded to handle a wide range of discreet and semi-discrete manufacturing systems with greater operational complexity. The schedule generator is based on Event-Scheduling/Time-Advance algorithm of discrete event systems simulation. Thus, in addition to time related performance measures (e.g. makespan), the schedule generator can be expanded to evaluate many performance measures such as work-in-process inventory, machine utilization, and workload balancing among others. These performance measures are ultimately affected by scheduling whereas traditionally scheduling models do not incorporate them. In generating a schedule, the schedule-generator is to be executed in a simulated time. Once an optimized schedule is in place, the schedule generator is to run in real time to become a supervisory controller and monitor the schedule and react for unexpected events. To achieve this, the proposed framework need to have database modules for integration with IT-infrastructure. The framework can also incorporate problem specific modelling capability, parallel computations and artificial intelligence (AI) for self-parameter tuning.

Initialize	• Get a Job-Release-Queue (JRQ) from the solution population (Left part of Fig. 1). • Set the current time $t_{current} = 0$
Step 1	• Is there is an Operation-Completion Event (o-j-m-t_{ojm}) at the top of the event list to occur at the current time (i.e. $t_{ojm} = t_{current}$)? If yes go to Step 2; Otherwise go to Step 3
Step 2	• Remove Event ($o - j - m - t_{ojm}$) from the top of the event list of the calendar. • Remove Operation ($o - j - t_{ojm}$) from the front of job queue of machine m. • If operation o of job j is not the last operation, assign operation $o + 1$ of this job to the alternative machine m' that can complete this operation at earliest time. Say the completion time is $t_{o+1,j,m'}$. • Append Operation ($[o + 1] - j - t_{o+1,jm'}$) at the tail of operations queue of machine m′ and insert Event ($[o + 1] - j - m - t_{o+1,jm'}$) in the calendar. Go to Step 1.
Step 3	• Are there machine(s) that are currently (at $t = t_{current}$) idle. If yes, go to Step 4. Otherwise Go to Step 7
Step 4	• If there is a job in the (JRQ), go to Step 5. Otherwise, go to Step 7.
Step 5	• Starting from the front the JRQ, look for a job whose first operation can be assigned to one of these idling machines. If there is such a job (j'), remove this job from JRQ and go to Step 6. Otherwise, go to Step 7
Step 6	• Among the idling machines that can process the first operation of job j', find the one that can finish this operation at the earliest time. Say this machine is machine m'' and the completion time is $t_{1,j',m''}$. Append operation ($1 - j' - t_{1,j'm''}$) to the empty queue of machine m''. Insert event ($1 - j' - m'' - t_{1,j'm''}$) in the calendar list. Go to Step 3
Step 7	• If the calendar list is not yet empty: advance the time to the time of the event at the top of the event list (say this event is $o - j - m - t_{ojm}$): $t_{current} = t_{ojm}$. Then, go to Step 2. Otherwise, go to Step 8
Step 8	• The JRQ is completed and the current time is the makespan ($Makespan = t_{current}$)
Next	• Start again from Initialize Step until all JRQ are evaluated.

Fig. 2: Steps of the schedule generator

4 Feasibility of the Proposed Methodology (A proof concept)

The research direction in Section 2.1 can be accomplished mainly through direct observation of real systems and surveys followed by critical analysis of the information gathered in order to develop new guidelines/frameworks for a generalized scheduling algorithm. As for the other research direction, the author conducted a preliminary study (as a proof of concept) to develop a unified meta-scheduling procedure based on the proposed framework for the job-shop and the flow shop problems described in Defersha and Chen (2010) and Defersha and Chen (2012), respectively. The generalized method was found to be comparable to (or better than) the specialized algorithms developed in those two articles. This clearly shows the feasibility of the methodology in achieving those objectives. Recently, the author has been also working in an industrial scheduling problem titled "Integrated Operations and Manpower Scheduling" in collaboration with a local industry. The manufacturing facility encompasses features from job-shop, flow-shop, unit processing, batch processing, assembly, among many others. The system is also very dynamic as it involves many small batch products with frequent changes in product mix and demand. The framework proposed in this research was followed to implement the concept of dynamic scheduling and supervisory control. The results demonstrate the feasibility of the methodology in pursuing the research direction in Sections 2.2, 2.3 and 2.4. Metaheuristics and time-advance-event-scheduling algorithm are individually proven to handle a wide range of problems in manufacturing systems analysis. This makes their combined use to be the most feasible choice in pursuing the proposed research directions.

5 Research Novelty and Anticipated Impacts

Though many researchers recognize the benefit of system independent scheduling tools, there are only few published attempts. Davis and Fox (1994) and McIlhagga (1997) both make initial attempts in developing a system independent scheduling frameworks, but fall short in terms of generality and flexibility of the frameworks they propose. Smith and Becker (1997) and Kostas et al. (2001) create unified scheduling ontologies, but the ontologies are not well suited for an easy problem representation and solution encoding and not suitable for optimization. A scheduling methodology that can be used across domains (job-shop, traveling sales man, vehicle routing) was patented by Montana and Herrero (2000) and presented in Montana (2001). However, the approach lacks depth in each domain and cannot address the challenges of today's complex manufacturing systems. Framinan and Ruiz (2010, 2012) provide guidelines and architecture for unified scheduling tools. However, the authors provide broad-brush approaches on the problem and lacks specific algorithm development. The research proposed in this article is unique and novel in developing a scheduling algorithm that is more flexible to be used in wider range of manufacturing systems. This will enable ERP

developers incorporate detail scheduling functionalities in their software and also enable industries acquire automated scheduling tool without the need to develop expensive customized algorithms. On top of its generality, the proposed method is unique by enabling the optimization of many performance measures that are highly influenced by scheduling but not addressed in scheduling literature. The proposal is also unique by unifying supervisory control and schedule into a single tool to address the dynamic/stochastic nature of manufacturing systems.

6 Concluding Remarks

Technology, in the form of equipment and automation, has always been a means to competitiveness. However, an equally important and a determining avenue to competitiveness is the way we organize facilities, plan production and schedule operations. Production planning and scheduling has become a necessity for survival and its importance cannot be overstated. It is a critical decision making process of allocating limited resources to tasks over time, while many time and relationship constraints among the activities and resources are being satisfied.

A scheduling problem usually involves a very large number of variables and constraints and it is one of the very difficult combinatorial optimization problems known to the research community. To this end, it becomes an active field in operations research and countless number of articles are published in the area. However, most published articles are focused in developing models and algorithms for theoretical scheduling problems having well-defined structures such as job shop, flow shop, parallel machine shop and their variants. Whereas, scheduling in practice, varies greatly between different companies with no definitive model of "real world" scheduling available to aid manufacturing industries. Thus, applied research endeavors and their publications are very timely and much needed in solving realistic scheduling problems in wide range of industries.

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Modeling and Solving the Total Flow Time Fixed Group Shop Scheduling Problem

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Abstract. In this paper, we study a particular case of a Group Shop Scheduling that we call Fixed Group Shop Scheduling (FGSS). In a FGSS, each job has the same number of stages, and the operations for the job than must be processed at the stage in the k-th position share the same set of machines with the other jobs. To solve the FGSS, we applied a modified Tabu Search heuristic. Our contribution consists in adapting the well-known Giffler and Thompson algorithm embedded with a self-tuning mechanism that guarantees semi-active schedules. An empirical study of different approaches including constraint programming and mixed-integer linear programming exhibited competitive performance of our proposed approach.

Keywords: Scheduling, Fixed Group Shop, Constraint Programing, Metaheuristics.

1 Introduction

In this paper, we address a special case of a Group Shop Scheduling Problem (GSS) that we call Fixed Group Shop Scheduling (FGSS). An example of a FGSS consists in a mechanical workshop were routine car maintenance operations must be performed. Naturally, the number of operations for each job (*car*) j and their processing times depends on different factors as the odometer count and the time between maintenance. Indeed, for each car j the set of maintenance operations can be divided into stages where it is necessary to complete all the operations on stage s in an arbitrary order (i.e. change the air filter, change the motor oil, etc.) to continue to the following stage $s + 1$ (i.e. car's washing and cleaning), and so on. In this context, it is desirable to minimize the flow time of each car in the workshop to meet the customer's expectatives. Also, some setup operations may be required between two consecutive cars. Hence, we considerer setup times between two consecutive operations at each machine. To the best of our knowledge, the FGSS has not been studied before and for these characteristics and practical applications, we consider that it deserves dedicated attention.

The paper is organized as follows: section 2 corresponds to the literature review. Section 3 presents the FGSS. Section 4 describes the modified Tabu Search (mTS) and computational experiments. Section 5 concludes and proposes future work.

2 Literature Review

The GSS problem was first introduced in [1]. A GSS consists of a set of m different machines that perform operations of n jobs, where each job j has s_j stages of operations. A stage s_j consists of a subset of operations of a job j that can be processed in any arbitrary relative order, while the stages of a job must be processed in a predetermined order $1,2,\dots,s_j$ [2]. Almost most papers for the GSS focus on finding a solution that minimizes the makespan ([2], [3], [4], [5], [6]). The consideration of sequence-dependent setup and transportation times have been proposed as extensions for the GSS [7]. Additionally, other publications consider stochastics and/or fuzzy extensions for the GSS ([3]). The main metaheuristics used to solve the GSS are Genetic Algorithm ([2], [7]), Tabu Search ([2], [5], [6]) and Ant Colony Optimization ([4]).

3 Fixed Group Shop Scheduling Problem

In a FGSS environment, each job has the same number of stages, and the operations for the job than must be processed at the stage in the k-th position share the same set of machines with the other jobs. In Table 1 we give an example for the total flow time FGSS. The processing times for Job 1 (J_1) are 1, 3, 4, 2 and 1 at Machines $M_1 \dots M_5$, respectively. Moreover, operations O_1, O_2 y O_3 for J_1 belong to the Stage 1 (S_1), thus could be processed in an arbitrary order. Then, after finishing their operations at S_1, J_1 continues its process at S_2 and finally completes its process at S_3.

Table 1. Processing times of a small-sized instance for the FGSS.

Stages	S_1	S_1	S_1	S_2	S_3
Jobs / Machines	M_1	M_2	M_3	M_4	M_5
Job 1	1	3	4	2	1
Job 2	2	1	3	1	4
Job 3	3	2	1	4	2

In Fig. 1 we show two solutions for the FGSS instance proposed in Table 1. The disjunctive graph presented in Fig. 1 (Left) represents an arbitrary solution with $\sum_j F_j = 41$, where the red dotted directed arcs show the sequence at the machines. Analogously, the black dotted directed arcs show the groups-permutations (i.e. the route of operations for J_1 at S_1 is O_1, O_3 and O_2, then must follow the route $M_1 - M_3 - M_2$). In Fig. 1 (Right) we show a disjunctive graph corresponding to an optimal solution with $\sum_j F_j = 38$. For both solutions, we provide a Gantt chart representation.

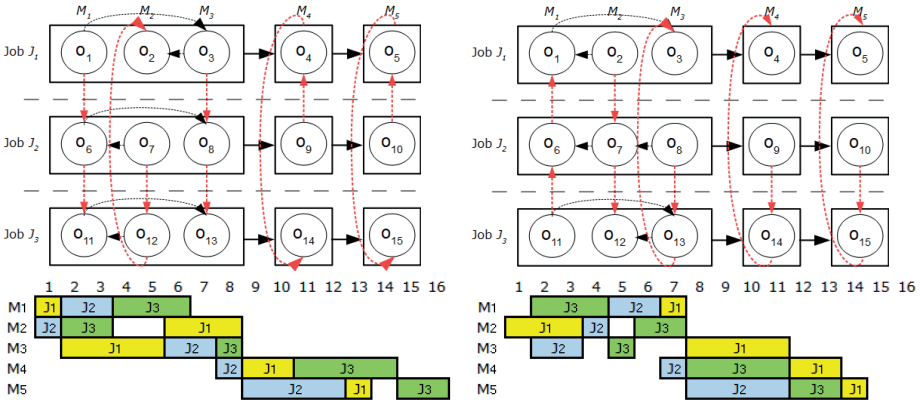

Fig. 1. (Left) An arbitrary feasible solution for the FGSS instance presented in Table 1 with $\sum_j F_j = 41$. (Right) An optimal solution for the FGSS instance presented in Table 1 with $\sum_j F_j = 38$.

4 Solution method

We propose a modified Tabu Search (mTS) that uses a permutation list representation. The eligible set of operations to be scheduled was chosen following the guidelines discussed in [8]. The well-known Giffler and Thompson (G&T) [9] appending algorithm in this context guarantees semi-active schedules. To avoid redundancy, we embedded in our mTS a mechanism that prevents a previously accepted schedule will be accepted again in a further iteration. To choose an operation to be scheduled from the eligible set we use the self-tuning approach proposed by [10]. All the experiments use as initial solution a permutation list provided by the Shortest Processing Time (SPT) dispatching rule. Finally, we use a swap as an operation movement. Preliminary computational experiments were tested on 40 instances from [10]. To adapt these instances to the FGSS, the operations of each job were assigned to a stage. Instances and detailed results could be consulted at: https://tinyurl.com/yxbwpq99.

4.1 Performance

The experiments were run on an Intel® Core™ i7-7500U CPU @ 2.70GHz processor with 16Gb RAM using the proposed mTS, MILP CPLEX 12.10, GUROBI 9.0.2, and the ILOG CPLEX ™ CP optimizer (12.10). The stopping criterion was a maximum running time established with the formula $jobs \times machines$ seconds. The performance measure was the Relative Percentage Deviation (RPD):

$$RPD = \frac{objective - bestObjective}{bestObjective} * 100\% \quad (1)$$

$objective$ is the value of the objective function of a given solution and $bestObjective$ was either the optimal value or the best-known solution (bks). The average (AVG) for the mST was obtained after running each instance 10 replicates with different seeds.

Table 2. RPD calculated over the randomly generated instances $FGSS_m/S_{jik}/\sum_j C_j$

Size	CP AUTO	CP DF	CP RS	CP MP	CP ID	CPLEX 12.10	GUROBI 9.0.2	mTS BEST	mTS AVG
4×4	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**	**0.00%**
5×5	**0.00%**	1.56%	**0.00%**	0.24%	2.84%	**0.00%**	**0.00%**	**0.00%**	**0.00%**
7×7	1.38%	22.09%	1.03%	3.24%	5.72%	6.05%	7.63%	**0.00%**	0.97%
10×10	1.14%	36.23%	2.93%	3.80%	4.99%	10.95%	23.26%	0.25%	2.25%
Avg.	0.63%	14.97%	0.99%	1.82%	3.39%	4.25%	7.72%	**0.06%**	**0.81%**

For instances of 4x4 and 5x5, all the approaches reach the optimum. For instances of 7x7 and 10x10 the optimum could not be verified, thus the RPD was calculated over bks. In this case, the MILP approach was outperformed by both, CP and mTS. Finally, our mTS exhibited competitive performance in contrast with the CP approach.

5 Conclusions and future works

The preliminary computational results show consistency and competitiveness of our mTS to solve the total flow time FGSS with sequence-dependent setup times compared with CP and MILP. However, more computational experiments are needed with larger instances. As a future work, we consider exploring other schedule generation schemes that guarantee an active schedule in the presence of setup times.

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Production Planning with Remanufacturing and Environmental Costs

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Abstract. In this paper we address an extension of the economic lot-sizing problem with remanufacturing, in which environmental costs are considered in the objective function in addition to the traditional economic costs. Separate costs for emissions, water and energy consumptions are assumed for the manufacturing and remanufacturing activities as well as to carry on positive inventories of both used and serviceable products. We provide a mixed-integer linear programming formulation for the problem and suggest several solving procedures based on the Tabu Search metaheuristic. In order to evaluate the suggested procedures, we compare them against an optimization solver over a benchmark set of instances of the literature extended for the problem. From the results obtained of the numerical experimentation, we can conclude that the suggested procedures are able to achieve near optimal solutions in a time-effective way. This effect is particularly significant for large instances of the problem. In addition, we consider an objective function with weighted costs, in order to analyze the effect of including environmental costs in the hybrid production-remanufacturing systems.

Keywords: Lot-sizing problems, Remanufacturing, Environmental costs, Optimization, Heuristics, Tabu Search.

1 Introduction

Production planning is crucial for industrial companies [1]. The basic production problem involves to determine how much and when to produce of a certain product in order to fulfill the demand requirements on time, minimizing the sum of the involved costs of production and storage. This problem is commonly known in the literature as the Economic Lot Sizing Problem (ELSP) [2].

Manufacturing has an impact on the planet's ecology. The emissions coming from the processing and use of fossil fuels that reach the atmosphere and the industrial garbage impact all forms of life around the world, causing irreversible damage to the ecosystem. These are just some of the environmental problems caused by pollution from factories [1, 3].

Circular Economy is an alternative that promotes to change the traditional linear production model consisting on producing, using and discarding, for one where used products are reincorporated at the first phase of the production cycle. It proposes to recover and restore used products, components and materials applying strategies such as reuse, repair and remanufacturing [4].

Remanufacturing is an industrial recovery process of used product which guarantees that a recovered product offers at least the same functionalities as a new one [5]. To achieve this goal, it goes through different stages that involves dismantling the product, restoring and replacing components and testing the individual parts and the whole product to ensure that it is within its original design specifications.

Taking into account the aforementioned, it is important to note that the focus should not only be on reducing economic costs of the production process but also on minimizing the negative impact on the environmental of their activities. This can be achieved by redesigning the production cycle of factories to focus on more environmentally friendly strategies such as collecting and remanufacturing used products.

Regarding production planning, we note that Wagner and Whitin [2] were the first to suggest an efficient algorithm for the ELSP. It is based on a dynamic programming approach of computational complexity $O(n^2)$, with n the number of periods. Zangwill [6] extended the algorithm for the case of general concave costs and Hanafizadeh et al. [7] extended with uncertain costs. In 1993, Aggarwal and Park [8] developed a more efficient algorithm of $O(n \log n)$ time.

A relative recently extension of the ELSP is to consider the remanufacturing of used products returned to the origin in order to satisfy the demand requirements. This problem extension is known in the literature as the Economic Lot Sizing Problem with Remanufacturing (ELSR). Teunter et al. [9] analyze this problem, suggesting a Mixed Integer-Linear Programming (MILP) formulation for the cases of joint and separate set-up scheme. In addition, the Silver-Meal (SM), Minimum Unit Cost (LUC) and Fragmented Period Balancing (PPB) heuristics are adapted for the problem. Piñeyro and Viera [10] tackle the ELSR with disposal options. A Basic Tabu Search (BTS) based-on procedure is proposed and evaluated. In Piñeyro and Viera [11] the performance of the BTS procedure is improved by means of applying a property on the form of the ELSR optimal solutions.

Absi et al. [12] and Retel Helmrich et al. [13], describe that in recent years, a significant effort has been made to mitigate the environmental impact of industrial processes. For instance, the United Nations Kyoto Protocol in 1998 [14], and the European Commission's emissions trading legislation in 2010 [15]. In Retel Helmrich et al. [13], the emission in both the set-up and the inventory holding costs are studied for the ELSP. To solve the problem, they suggest a Lagrangean heuristic and a Polynomial-Time Approximation Scheme (FTPAS) based-on algorithm.

The Cap-and-Trade emerged as a public policy to counteract CO_2 emissions, offering economic incentives for those who manage to reduce them. Benjaafar et al. [16] and Akbalik and Rapine [17] suggest and study models for exploring this concept. In Benjaafar et al. [16] and Yuan et al. [18], the concept of Certified Emission Reduction (CER) is also incorporated in order to reduce the carbon emissions.

The problem of lot-sizing that incorporates remanufacturing options under a carbon emission constraint is considered by Zouadi et al. [19, 20]. Piñeyro and Viera [21] consider the ELSR with recovery targets established as a percentage of the total returns that must be remanufactured. Establishing a recovery target may be a mechanism to reduce the negative impact of the new item manufacturing activity. Rapine et al. [22] also tackle a production system with capacity constraints and environmental considerations. The objective is to minimize the sum of all the costs involved and the use of energy established as a non-linear function. Giglio et al. [23] address an integrated lot sizing and energy-efficient job shop scheduling problem, minimizing the sum of the economic costs and the energy costs related to the utilization of machines and processing times. Finally, Heck and Schmidt [1] identify three relevant factors to minimize the environmental impact in a production system: energy use, carbon emissions and water consumption. A mathematical model is defined with an objective function that includes the cost of energy, emissions and water usage in addition to the economic costs of production.

In this paper we propose a MILP formulation for the ELSR considering environmental costs in addition to the traditional economic costs. The main difference with the problem addressed in Zouadi et al. [19, 20] is that we consider not only emissions, but also water and energy consumption. In addition, we relax the upper bounds on the emissions, since it is considered as part of the environmental costs.

For this ELSR extension, three heuristic procedures based on the Tabu Search metaheuristic are suggested and evaluated by means of a benchmark set of ELSR instances adapted to this problem. The suggested procedures are based on the BTS procedure introduced in Piñeyro and Viera [10] for the ELSR, extending it to consider environmental costs as well as other strategies for the exploration phase.

The rest of the paper is organized as follows. Section 2 provides the problem definition and the mathematical model for the ELSR extension under consideration. Section 3 addresses the description of the solution procedures suggested for the problem. The numerical experimentation and the analysis of the results obtained are provided in Section 4. Conclusions and possible directions for future research are given in Section 5.

2 Problem definition

We address a hybrid production-remanufacturing system of a single product in which the demand must be satisfied on time by either the production of new items or remanufacturing used ones returned to the origin, i.e., remanufactured products look as-good-as new. Henceforth, the terms return and used product, as well as production and manufacturing, are used interchangeably. Demand and returns values are assumed non-negative integers known in advance for each one of the periods within the finite planning horizon. Economic and environmental costs are assumed for manufacturing and remanufacturing, as well as for the inventory of serviceable and used products. Three types of environmental costs are considered: water consumption costs, energy consumption

costs and emissions costs. Set-up costs are assumed for both manufacturing and remanufacturing, and linear costs for holding inventory of both used and serviceable products. The objective is to determine the quantities to produce and remanufacture at each period in order to minimize the sum of the economic and environmental costs.

The notation used for the problem is listed below.

- Parameters:
  - n: number of periods, with $n > 0$.
  - $T = \{1, ..., n\}$: set of periods within the planning horizon.
  - D_t: serviceable items demanded in period $t \in T$.
  - R_t: used items returned in period $t \in T$.
  - h_t^r: economic unit cost of holding used inventory in period $t \in T$.
  - h_{at}^r: water consumption unit cost of holding used inventory in period $t \in T$.
  - h_{ct}^r: emissions unit cost of holding used inventory in period $t \in T$.
  - h_{et}^r: energy unit cost of holding used inventory in period $t \in T$.
  - h_t^s: economic unit cost of holding serviceable inventory in period $t \in T$.
  - h_{at}^s: water consumption unit cost of holding serviceable inventory in period $t \in T$.
  - h_{ct}^s: emissions unit cost of holding serviceable inventory in period $t \in T$.
  - h_{et}^s: energy unit cost of holding serviceable inventory in period $t \in T$.
  - K_t^m: economic set-up cost for manufacturing in period $t \in T$.
  - K_{at}^m: water set-up cost for manufacturing in period $t \in T$.
  - K_{ct}^m: emissions set-up cost for manufacturing in period $t \in T$.
  - K_{et}^m: energy set-up cost for manufacturing in period $t \in T$.
  - K_t^r: economic set-up cost for remanufacturing in period $t \in T$.
  - K_{at}^r: water set-up cost for remanufacturing in period $t \in T$.
  - K_{ct}^r: emissions set-up cost for remanufacturing in period $t \in T$.
  - K_{et}^r: energy set-up cost for remanufacturing in period $t \in T$.
  - M: big number.
- Decision variables:
  - I_t^s: inventory level of serviceable products in period $t \in T \cup \{0\}$.
  - I_t^r: inventory level of returns in period $t \in T \cup \{0\}$.
  - x_t^m: number of items to manufacture in period $t \in T$.
  - x_t^r: number of items to remanufacture in period $t \in T$.
  - y_t^m: equal to 1 if there is manufacturing in period $t \in T$, 0 otherwise.
  - y_t^r: equal to 1 if there is remanufacturing in period $t \in T$, 0 otherwise.

We refer to the hybrid system described above as the Economic Lot-Sizing Problem with Remanufacturing and Environmental Costs (ELSR-EC). It can be formulated as the following MILP, extending those suggested for the ELSR in [9, 11]:

$$\min \sum_{t \in T} \Big\{ \left(K_t^m y_t^m + K_t^r y_t^r + h_t^s I_t^s + h_t^r I_t^r\right) + \left(K_{et}^m y_t^m + K_{et}^r y_t^r + h_{et}^s I_t^s + h_{et}^r I_t^r\right) + \left(K_{ct}^m y_t^m + K_{ct}^r y_t^r + h_{ct}^s I_t^s + h_{ct}^r I_t^r\right) + \left(K_{at}^m y_t^m + K_{at}^r y_t^r + h_{at}^s I_t^s + h_{at}^r I_t^r\right) \Big\} \quad (1)$$

subject to:

$$I_t^s = I_{(t\text{-}1)}^s + x_t^r + x_t^m - D_t, \quad \forall t \in T \tag{2}$$

$$I_t^r = I_{(t\text{-}1)}^r + R_t - x_t^r, \quad \forall t \in T \tag{3}$$

$$x_t^m \leq M y_t^m, \quad \forall t \in T \tag{4}$$

$$x_t^r \leq M y_t^r, \quad \forall t \in T \tag{5}$$

$$I_0^s = I_0^r = 0 \tag{6}$$

$$y_t^m, y_t^r \in \{0, 1\}, \quad \forall t \in T \tag{7}$$

$$x_t^m, x_t^r, I_t^s, I_t^r \geq 0, \quad \forall t \in T \tag{8}$$

Objective function (1) is composed by four components: economic costs, energy consumption costs, emissions costs and water consumption costs. Equations (2) and (3) are the inventory balance equations for serviceable and used products, respectively. Constraints (4) and (5) state that the binary variables related to the set-up costs for production and remanufacturing must be equal to 1 if a positive amount is produced or remanufactured, respectively. Constraint (6) establishes that the initial inventory level for both serviceable and used products is assumed equal to zero. Finally, constraints (7) and (8) define the domain for the decision variables of the problem.

3 Heuristic procedures for the ELSR-EC

In this section we present the main solving procedure and its variants, suggested for the ELSR-EC. The procedure TS-EC (Tabu Search with Environmental Costs) is based on the Tabu Search metaheuristic (Glover et al. [24]). This metaheuristic is an iterative exploration process based on information stored in memory (tabu list) to allow to escape from local optimal of optimization problems. In the following subsections the different components of TS-EC will be explained. This procedure can be considered an extension of the BTS procedure proposed by Piñeyro and Viera [10] for the ELSR.

3.1 TS-EC procedure

A feasible solution of the ELSR-EC is represented as a pair of (0,1) n-tuples, one for indicating the positive periods of remanufacturing and the other for the positive periods of manufacturing. A value 1 in position t of the remanufacturing (manufacturing) in the n-tuple means remanufacturing (manufacturing) can be positive in period t, with $1 \leq t \leq n$. On the other hand, a value 0 in position t means remanufacturing (manufacturing) must be zero.

The TS-EC procedure consists of the following phases:

- **Initial phase**: the initial n-tuple of the remanufacturing plan is generated.

- **Generation phase**: given the *n*-tuple of the remanufacturing periods, the remanufacturing amounts are determined and then, the optimal production plan (periods and quantities) is obtained.
- **Exploration phase**: given the feasible ELSR-EC solution from the previous phase, a new solution is sought among its neighbors, with lower ecological and economic costs than the given (or current) solution.

For the initial phase, we use a value of zero for every position of the *n*-tuple of the remanufacturing plan, i.e. zero remanufacturing. Given the *n*-tuple of the remanufacturing plan, the generation phase is performed in order to determine a feasible solution for the ELSR-EC. The remanufacturing plan is determined according to the following rule also used in [10]:

$$x_i^r = min\ \{I_{i-1}^r + R_i,\ D_{i,(j-1)}\}\ \forall 1 \leq i < j \leq n+1 \tag{9}$$

$$D_{i,(j-1)} = \sum_i^{j-1} D_k \tag{10}$$

Equation (9) means that the remanufacturing quantity of a period *i* is determined as the minimum between the number of available returns in period *i* and the accumulated demand, described in (10), until the preceding period of the period *j* fixed as the next period of positive remanufacturing. We note that the optimal production plan can be obtained from a given remanufacturing plan [10]. The algorithm of Wagner and Whitin [2] was adapted to consider the initial inventory of serviceable products and the environmental costs of the production activity.

Finally, the exploration phase is performed with the aim to improve the feasible solution of the ELSR-EC obtained from the generation phase. First the neighbors of the remanufacturing *n*-tuple are determined by means of a Hamming distance of 1 (swap moves). It is checked that each neighbor does not belong to the tabu list. We consider a limited size tabu list managed according to the FIFO rule (First in First Out). A new candidate solution for the problem is determined using the procedure of the generation phase. The exploration phase runs until the stop condition is reached: the number of iterations is greater than a certain maximum value. The solution with the lowest economic and environmental cost of all the evaluated solutions, is returned.

3.2 TS-EC variants

In order to make the exploration phase of the TS-EC more diverse, we develop two variants of the procedure by means of the jump transformation defined as follows. Given a feasible solution of the ELSR-EC, a jump is defined as a shift of certain number of components of the *n*-tuple of its remanufacturing plan, from 0 to 1 or vice versa. The following jump transformations are used in this paper:

- Negative: all components from 1 to *n* of the remanufacturing *n*-tuple are shifted.
- Random: a random number of the components of the remanufacturing *n*-tuple are shifted.

We refer as TS-ECNO and TS-ECRO to the TS-EC variants with the negative and the random jump transformations, respectively. The following pseudocode presents an outline of the new procedures.

```
jumpCount = 0;
remanufacturingTuple = zeroTuple;
solution = TS-EC(remanufacturingTuple);
while (jumpCount < jumpCountMax) {
  remanufacturingTuple = solution.remanufacturingTuple()
  if (variant == TS-ECNO) {
    transformedTuple = Negative(remanufacturingTuple);
  }
  if (variant == TS-ECRO) {
    transformedTuple = Random(k, remanufacturingTuple);
  }
  solution = TS-EC(transformedTuple);
  jumpCount ++
}
```

We note that the Random () function in the pseudocode of above receives the number k of components of the remanufacturing n-tuple to be shifted. The position of each component is determined randomly.

4 Numerical experimentation

In this section we provide the results of the numerical experimentation carried out to evaluate the performance of the heuristic procedures presented in the previous section. The cost gap between the solution obtained from the heuristics and that from AMPL/CPLEX, is calculated as follows:

$$cost\ gap = \frac{heuristic\ cost - exact\ method\ cost}{exact\ method\ cost} \times 100 \tag{11}$$

The parameter values were generated according to a uniform distribution (UD), considering the ranges suggested by Retel Helmrich et al. [13]. We consider two different scenarios for returns and set-up costs of remanufacturing, “Low” and “High”. In order to facilitate the comparison of the results, the unit production and remanufacturing costs are assumed zero.

- Demand (D_t): UD(100, 200).
- Returns (R_t): UD(0, 100) and UD(100, 200).
- Set-up cost for production (K_t^m,$\hat{K}_{at}^m$,$\hat{K}_{ct}^m$,$\hat{K}_{et}^m$): UD(2500, 7500).
- Set-up cost for remanufacturing (K_t^r,$\hat{K}_{at}^r$,$\hat{K}_{ct}^r$,$\hat{K}_{et}^r$): UD(500, 1500) and UD(2500, 7500).
- Inventory cost for final products (h_t^s,$\hat{h}_{at}^s$,$\hat{h}_{ct}^s$,$\hat{h}_{et}^s$): UD(10, 20).
- Inventory cost for returns (h_t^r,$\hat{h}_{at}^r$,h_{ct}^r,$\hat{h}_{et}^r$): UD(0, 10) y DU(10, 20).

We note that there are 512 different configurations of parameter values. For each configuration we generate 10 different instances, which results in 5,120 instances in total. The number of periods (n) is equal to 20 for all the instances.

It is important to note that TS-EC and TS-ECNO are deterministic, whereas TS-ECRO can give different results depending on the executions since the periods to be shifted are chosen randomly. Therefore, for the TS-ECRO we take the average value of three runs for each one of the instances.

There are also certain parameters that are specific to the heuristics, which are listed below:

- MAX_ITER: number of iterations for the exploration phase.
- MAX_JUMPS: number of jumps transformation to be performed.
- LIST_SIZE: number of n-tuples to be stored in the tabu list.
- RANDOM_NUM: number of periods to be shifted at the remanufacturing n-tuple.

In Table 1 we provide the values chosen for the parameters of the heuristics. To achieve this, a preliminary study was carried out in 512 instances, comparing the results against CPLEX solver.

Table 1. Heuristic parameter values for $n = 20$.

	TS-EC	TS-ECNO	TS-ECRO
MAX_ITER	50	50	50
MAX_JUMPS	-	2	4
LIST_SIZE	1,000,000	1,000,000	1,000,000
RANDOM_NUM	-	-	16

All the numerical experiments were carried out on a 2.81Hz Windows 10 i7-7700HQ laptop, with 16GB RAM.

4.1 Performance analysis for $n = 20$

Tables 2 and 3 show the results for the costs gap and runtimes (in milliseconds) of the numerical experimentation. The first three columns in Table 1 describe the scenario (for example: Setup – Economic – High scenario). Then, there are columns for reporting the average, median, standard deviation and maximum values for the heuristics. Table 3 also includes the runtimes of CPLEX.

Table 2. Cost gaps for $n = 20$.

			Average			Median			Standard deviation			Maximum		
			TS-EC	TS-ECNO	TS-ECRO	TS-EC	TS-ECNO	TS-ECRO	TS-EC	TS-ECNO	TS-ECRO	TS-EC	TS-ECNO	TS-ECRO
All instances			1.2%	0.7%	0.8%	0.6%	0.4%	0.4%	0.4%	0.2%	0.3%	36.9%	12.9%	12.9%
Returns		Low	0.8%	0.5%	0.5%	0.5%	0.3%	0.3%	0.8%	0.6%	0.5%	5.1%	4.3%	4.3%
		High	1.6%	1.0%	0.9%	0.8%	0.6%	0.5%	2.7%	1.3%	1.2%	36.9%	12.9%	12.9%
Setup	Economic	Low	1.3%	0.8%	0.8%	0.7%	0.5%	0.5%	2.3%	1.2%	1.1%	31.6%	12.9%	12.9%
		High	1.1%	0.6%	0.6%	0.6%	0.4%	0.4%	1.8%	0.8%	0.7%	36.9%	12.5%	7.1%
	Water	Low	1.3%	0.9%	0.8%	0.7%	0.5%	0.5%	2.3%	1.2%	1.1%	36.9%	12.9%	12.9%
		High	1.1%	0.6%	0.5%	0.6%	0.4%	0.3%	1.7%	0.8%	0.7%	27.9%	12.5%	7.9%
	Energy	Low	1.3%	0.9%	0.8%	0.7%	0.5%	0.5%	2.3%	1.2%	1.2%	36.9%	12.9%	12.9%
		High	1.1%	0.6%	0.5%	0.6%	0.4%	0.3%	1.8%	0.7%	0.6%	29.1%	6.7%	4.5%
	Emitions	Low	1.3%	0.9%	0.8%	0.7%	0.5%	0.5%	2.3%	1.2%	1.1%	36.9%	12.9%	12.9%
		High	1.1%	0.6%	0.5%	0.6%	0.4%	0.3%	1.8%	0.8%	0.6%	31.6%	7.1%	6.5%
Inv.	Economic	Low	1.3%	0.8%	0.8%	0.7%	0.5%	0.5%	2.0%	1.1%	1.0%	29.1%	12.9%	12.9%
		High	1.0%	0.6%	0.6%	0.5%	0.4%	0.3%	2.1%	0.9%	0.8%	36.9%	9.1%	9.1%
	Water	Low	1.3%	0.9%	0.8%	0.7%	0.5%	0.5%	2.2%	1.2%	1.1%	28.4%	12.9%	12.9%
		High	1.0%	0.6%	0.6%	0.6%	0.4%	0.3%	1.9%	0.8%	0.7%	36.9%	12.5%	5.9%
	Energy	Low	1.4%	0.9%	2.4%	0.7%	0.6%	2.4%	2.4%	1.1%	0.0%	36.9%	12.9%	2.4%
		High	1.0%	0.6%	0.6%	0.5%	0.4%	0.3%	1.7%	0.8%	0.8%	29.1%	11.4%	11.4%
	Emitions	Low	1.3%	0.9%	0.8%	0.8%	0.5%	0.5%	2.1%	1.2%	1.1%	36.9%	12.9%	12.9%
		High	1.0%	0.6%	0.6%	0.5%	0.4%	0.3%	2.0%	0.8%	0.7%	31.6%	10.6%	10.6%

From Table 2 we can observe that the solutions found by the heuristics are similar to those found by CPLEX, with an average gap less than 1.5%. Then, we can conclude that the three heuristics are competitive with CPLEX.

Regarding the standard deviation in Table 3, we can note that the solutions found by CPLEX show a greater dispersion in terms of running time than the solutions from the heuristics.

Table 3. Running times (ms) for $n = 20$.

			Average				Median				Standard deviation				Maximum			
			CPLEX	TS-EC	TS-ECNO	TS-ECRO	CPLEX	TS-EC	TS-ECNO	TS-ECRO	CPLEX	TS-EC	TS-ECNO	TS-ECRO	CPLEX	TS-EC	TS-ECNO	TS-ECRO
All instances			339	81	245	359	290	73	218	349	32	11	44	9	2500	716	1219	1473
Returns		Low	452	80	250	342	422	81	246	336	205	13	21	26	2000	435	616	853
		High	305	68	199	361	266	67	198	350	193	9	13	38	1000	315	426	665
Setup	Economic	Low	300	86	232	341	266	82	237	334	186	21	25	30	1000	459	615	922
		High	374	72	209	366	344	70	208	353	208	13	19	49	1125	406	553	798
	Water	Low	275	76	218	380	250	73	212	394	170	15	25	46	1063	398	560	886
		High	361	84	238	359	328	81	241	339	206	20	28	52	1000	432	786	898
	Energy	Low	258	77	212	354	219	72	202	346	177	19	29	35	1094	473	599	790
		High	336	84	240	336	297	82	239	328	196	24	50	38	1047	650	991	911
	Emitions	Low	259	72	202	366	218	68	199	355	183	16	23	45	1984	385	653	802
		High	334	69	207	338	282	67	203	333	197	13	22	40	1032	315	502	1473
Inv.	Economic	Low	269	86	245	357	219	83	244	347	175	15	29	39	1093	380	741	804
		High	278	77	225	345	234	74	220	340	179	14	27	28	1125	377	703	694
	Water	Low	317	76	258	392	266	73	215	401	204	14	107	55	1250	392	1011	939
		High	352	73	212	371	297	71	210	363	225	13	19	42	1407	335	611	811
	Energy	Low	421	101	422	373	359	81	446	358	279	49	134	50	2500	716	1175	1023
		High	431	72	217	358	375	69	212	346	277	14	31	40	1797	380	822	887
	Emitions	Low	353	116	339	375	297	104	243	359	232	43	157	45	1500	508	1219	811
		High	431	90	286	356	375	72	220	355	248	40	110	25	2093	711	854	861

From Tables 2 and 3, we conclude that TS-ECNO and TS-ECRO variants outperform the TS-EC original heuristic in terms of cost gaps. In addition, we note that in average, TS-ECNO achieves the best results in terms of both, cost gaps and running times. In general, we also can conclude that the three heuristics are competitive compared to the CPLEX solver.

4.2 Cost weighting analysis

We note that the objective function of ELSR-EC considers the sum of the economic and environmental costs. However, environmental costs are composed by set-up costs

for emissions, energy and water consumptions. In this section we update the costs as follows: environmental costs are multiplied by α and the economic costs by β, with $0 \leq \alpha, \beta \leq 1$, in order to analyze the solutions under different weights on the cost components of the objective function. We consider 512 instances (one per configuration) and the TS-ECNO heuristic.

In Table 4 we summarize the results obtained. First column presents the different weights of the costs considered. The rest of the columns present the difference between the economic cost of the weighted function and the economic cost of the original function for all the measurements (average, median, standard deviation and maximum). The same is shown for the environmental costs.

Table 4. Weighted cost results for TS-ECNO compared to AMPL/CPLEX.

Weights	Average		Median		Standard deviation		Maximum	
	Gap cost Econ. (%)	Gap cost Env. (%)	Gap cost Econ. (%)	Gap cost Env. (%)	Gap cost Econ. (%)	Gap cost Env. (%)	Gap cost Econ. (%)	Gap Cost Env. (%)
α = 0, β = 1	-7.759%	13.874%	-6.977%	9.585%	6.380%	18.980%	-42.854%	197.415%
α = 1/3, β = 1	-4.604%	3.199%	-3.052%	1.810%	5.529%	4.659%	-32.299%	49.587%
α = 1, β = 0	6.979%	-1.026%	4.252%	-0.475%	9.551%	1.749%	95.380%	-13.794%

For the case ($\alpha = 0, \beta = 1$), only the economic costs are minimized. Analyzing the results in the average case, we note that the environmental costs increase around 14% with a maximum increase of 197.4%. Therefore, we can conclude that not including environmental costs in the objective function can cause a significant ecological impact. On the other hand, the economic cost in average decreases around 8% compared to the problem with the original cost function, i.e., $\alpha = \beta = 1$.

Since the environmental costs have three components (water, energy and emission), the case ($\alpha = 1/3$, $\beta = 1$) is intended to balance the weight of the three environmental aspects and of the economic costs. We note that the average of environmental cost increases only 3.2% with respect to the original objective function. In the opposite direction, is observed for the economic costs. However, the impact of reducing the weight of the environmental costs may be significant as it can be seen in the maximum gaps.

Finally, for the last scenario ($\alpha = 1$, $\beta = 0$) with only environmental costs in the objective function, we note the economic costs increase in average near to 7%, but the maximum gap is 95%. In addition, the benefits on the environmental side are only 1%.

4.3 Performance analysis for $n = 70$

Given the good performance obtained for the three heuristics for the case of 20 periods, we decided to evaluate them for large instances of 70 periods. Because of the size of the problem with 70 periods, we consider only 14 instances chosen arbitrary from the 512 configurations defined at the beginning of Section 4. The values of the parameters for the heuristic procedures are reported in Table 5 (the format is the same as Table 1).

Table 5. Heuristic parameter values for $n = 70$.

	TS-EC	TS-ECNO	TS-ECRO
MAX_ITER	15	15	15
	25	25	25
	35	35	35
	45	45	45
MAX_JUMPS	-	2	4
LIST_SIZE	1,000,000	1,000,000	1,000,000
RANDOM_NUM	-	-	16

In Table 6 we present the results obtained from the heuristics for the 14 large instances. First column indicates the name of the solving procedure and the second column the maximum number of iterations for the heuristic procedures. The rest of the columns are for the cost gaps and runtimes (average, median, deviation and maximum).

Table 6. Cost gaps and runtimes for $n = 70$.

	Iterations	Average		Median		Standard deviation		Maximum	
		Cost gap (%)	Runtime (m)	Cost gap (%)	Runtime (m)	Cost gap (%)	Runtime (m)	Cost gap (%)	Runtime (m)
CPLEX	-	0.000%	2.543	0.000%	0.684	0.000%	4.443	0.000%	15.087
TS-EC	15	12.945%	0.107	8.186%	0.103	18.098%	0.007	79.969%	0.123
	25	3.544%	0.207	2.183%	0.206	5.037%	0.008	22.270%	0.227
	35	2.350%	0.254	1.876%	0.253	2.165%	0.009	10.129%	0.276
	45	2.248%	0.440	1.876%	0.439	1.828%	0.004	8.706%	0.452
TS-ECNO	15	8.365%	0.372	8.186%	0.373	2.698%	0.010	12.000%	0.386
	25	2.826%	0.536	2.183%	0.534	1.003%	0.007	5.529%	0.555
	35	2.130%	0.764	1.876%	0.757	1.394%	0.038	6.833%	0.900
	45	2.058%	1.104	1.876%	1.103	1.204%	0.005	5.941%	1.120
TS-ECRO	15	1.880%	0.619	1.751%	0.623	0.681%	0.021	3.850%	0.641
	25	1.251%	1.439	1.182%	0.936	0.624%	0.029	3.264%	1.003
	35	1.204%	1.439	1.206%	1.254	0.724%	0.669	3.474%	3.941
	45	1.121%	1.766	0.971%	1.766	0.718%	0.031	3.496%	1.833

Considering the average values of Table 6 we can conclude that the suggested heuristics are competitive with CPLEX. In particular, for both the 35 and 45 iterations cases, we can observe that TS-ECRO achieves the lowest cost gaps (1.204% for 35 iterations and 1.121% for 45 iterations) in a less running time than CPLEX (1.439 and 1.766 versus 2.543 minutes, respectively).

5 Conclusions and future research

In this paper we address the economic lot-sizing problem with remanufacturing, considering environmental costs in addition to the traditional economic costs. We provide a MILP formulation for the problem and suggest three heuristic procedures based on the Tabu Search metaheuristic to solve it. To evaluate their performance, we compare them against AMPL/CPLEX, considering both costs and running times of the solutions.

Although the three heuristic procedures, TS-EC, TS-ECNO and TS-ECRO, show a good performance compared to the CPLEX solver, we note that for small and medium size instances, TS-ECNO achieves the best performance, considering the balance between runtime and cost gaps. On the other hand, for large instances, TS-ECRO achieves the best performance probably due to its random nature. In particular, we note that for the large instances the average runtimes for all procedures are significantly lower than those of CPLEX. In addition, the runtimes of the heuristic procedures are more stable, since their standard deviation is less than that obtained from the solver.

In order to improve the performance of heuristic procedures, we can modify the stop condition considering a maximum number of iterations without improvements instead of the total number of iterations as it is currently done. Another possible way to improve the procedures may be to analyze the form of the optimal solutions of the ELSR-EC as in Piñeyro and Viera [11] for the ELSR. Regarding the model, we observe that the objective function considered is the sum of the economic and environmental costs. A more realistic approach would be to consider a multi-objective function or even a multi-level model to better represent the relationship between economic and environmental costs.

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Simultaneous lot-sizing and scheduling with recovery options: problem formulation and analysis of the single-product case

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Abstract. We address an extension of the discrete lot-sizing and scheduling problem in which the demand of products can be also satisfied by remanufacturing used products returned to the origin. A mixed-integer linear programming formulation is provided for the problem, assuming dynamic demand and returns values, and time-invariant costs of setup and holding inventory. We then present a numerical experimentation carried out with the mathematical model for the case of a single product, in order to evaluate the efficiency in both costs and solving times compared to the traditional problem without returns. From the results obtained we conclude that the problem with recovery options can lead to economic benefits only under certain assumptions on the costs and amounts of returns. In addition, according to the runtimes obtained for large instances of the problem, it seems to be much more difficult to solve than its traditional version without returns.

Keywords: lot-sizing, scheduling, remanufacturing, mathematical programming, optimization

1 Introduction

The discrete lot-sizing and scheduling problem (DLSP) refers to the problem of simultaneously determining the lots and sequence of production for a set of products, in order to meet the demand requirements on time, minimizing the sum of production and inventory holding costs. Unlike other lot-sizing problems, in the DLSP only one item can be produced at each period and the production process runs at full capacity, i.e., small bucket periods and all-or-nothing production policy are assumed. Therefore, the quantity of production in a period established as a positive production period is determined based on a certain production speed

expressed in units per period. In addition, setup costs are only incurred when there is product changeover, i.e., configuration costs of the production line are only incurred at the beginning of the production process of a product.

A mixed-integer linear programming (MILP) and a heuristic solving approach for the DLSP in the case of a single machine is proposed in [3]. In [4] the DLSP with sequence-dependent setup costs is formulated and analyzed. Salomon et al. in [17] present a classification scheme and complexity results for the DLSP. In particular, they demonstrated that the DLSP with stationary costs, positive setup costs and single machine is NP-hard. However, they note that the DLSP for a single product can be efficiently solved as in [8] and [24]. Several extensions and solving approaches have been proposed in the literature for the DLSP, such as [23] for costs with non-speculative motives and [7] for start-up times and backlogging in the context of a tire curing scheduling problem. More recently, the DLSP with sequence-dependent changeover costs and time is addressed in in [5]. Bi-objective formulations for the DLSP considering carbon emissions and renewable energy are presented in [10]. We refer the readers to [1] and [25] for recent surveys about the DLSP and extensions.

In recent years, the circular economy (CE) paradigm has emerged as an alternative to face the negative impact on the environment of the traditional linear model of producing, consuming and disposing [21]. As a recovery option, remanufacturing can be considered a critical component of the CE as it attempts to maintain the value of used products (also called cores or returns) and to reduce the use of raw material and energy [9], thus achieving a win-win-win situation for producers, consumes and environment. Remanufacturing is an industrial process in which it is warrantied that a used product is returned to its original condition or even better. It often involves inspection, sorting, disassembling, cleaning, testing, reprocessing and reassembling tasks. Remanufacturable products include automotive parts, electric home appliances, personal computers, cellular phones, cameras, vending machines, among others [11]. In the field of production planning, we can find the seminal works of [15], [16] and [26] that extend the traditional economic lot-sizing problem (ELSP) in order to include returns flow and remanufacturing process. Teunter et al. [22] introduce the economic lot-sizing problem with remanufacturing (ELSR) with either joint or separate setup scheme. They provide an efficient algorithm for the joint case and extend the Silver-Meal heuristic for the problem. In [12] consider the ELSR with disposal of returns and in [18] suggest several improvements for the extended Silver-Meal heuristic. In [2], [19], [13] are suggested and evaluated different solving procedures for the ELSR based on metaheuristic approaches, and [14] considers the ELSR with recovery targets. We refer to [21] for a recent survey about production planning with recovery options.

In this paper, we extend the DLSP in order to include the returns flow, and assuming that demand can be also satisfied by remanufacturing used products. We refer to this problem extension as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). We provide a MILP formulation for the problem and present and analyze the results of a numerical experimentation

carried out in order to evaluate the efficiency in both costs and solving time of this hybrid production-remanufacturing system in the case of a single product. As far as we know, this DLSP extension has not been considered in the literature before. However, we note that there are some works that combine scheduling and remanufacturing, but for different problem assumptions [27], [6], [20].

The remainder of this paper is organized as follows. In Section 2 we present the description and the MILP formulation suggested for the problem under consideration. Section 3 provides the results and the analysis of the numerical experimentation carried out in order to evaluate the efficiency of the DLSR for the case of a single product. Finally, in Section 4 we present the conclusions and some possible directions for future research.

2 Problem description and formulation

The problem tackled in this paper can be stated as follows. We address a dynamic hybrid production-remanufacturing system with a single machine for processing $J > 0$ products under all-or-nothing production policy and over a finite planning horizon $T > 0$. Small-bucket periods are assumed. Therefore, only one product can be produced or remanufactured, but not both in the same period. The production and remanufacturing speeds for each product j, p_j and r_j respectively, are expressed as unit per period. Demand for a product j in a period t must be satisfied on time (backlogging is not allowed) from produced or remanufactured products generated in the same period (zero lead-time is assumed) or in a previous period and held in the inventory of serviceable products. Demand and returns values are assumed known in advance for each product and period over the planning horizon. Production and remanufacturing setup costs are incurred when there is product changeover. There are also linear costs for carrying on one unit of serviceable or used product from one period to the next one. Setup and inventory holding costs are assumed known and time-invariant. The objective is to determine the lots and sequence of products to be produced and remanufactured in order to satisfy the demand requirements on time, minimizing the sum of the costs involved.

Below we present the notation used for the problem from here and throughout the rest of the paper.

Sets and indices:

J : Number of products, with index $j \in \{1, ..., J\}$.
T : Number of periods, with index $t \in \{0, 1, ..., T\}$.

Parameters:

D_{jt} : Demand of product j in period $t > 0$.
R_{jt} : Returns of product j available in period $t > 0$.
K_j^p : Production setup cost of product j.
K_j^r : Remanufacturing setup cost of product j.
h_j^s : Holding cost for serviceable product j per unit and per period.
h_j^u : Holding cost for used product j per unit and per period.
p_j : Production speed for product j (units per period).
r_j : Remanufacturing speed for product j (units per period).

Variables:

I_{jt}^s : Inventory of serviceable product j at the end of period t.
I_{jt}^u : Inventory of used product j at the end of period t.
y_{jt}^p : $y_{jt}^p = 1$ indicates that product j is produced in period t;
$y_{jt}^p = 0$, otherwise.
y_{jt}^r : $y_{jt}^r = 1$ indicates that used product j is remanufactured in period t;
$y_{jt}^r = 0$, otherwise.
z_{jt}^p : $z_{jt}^p = 1$ indicates a production setup for product j in period $t > 0$;
$z_{jt}^p = 0$, otherwise.
z_{jt}^r : $z_{jt}^r = 1$ indicates a remanufacturing setup for product j in period $t > 0$;
$z_{jt}^r = 0$, otherwise.

Based on the notation of above, the DLSR can be formulated as the following MILP. We note that it can be considered an extension of that introduced in [8] and [24] for the DLSP.

$$\min \quad \sum_{j=1}^{J}\sum_{t=1}^{T}(K_j^p z_{jt}^p + K_j^r z_{jt}^r + h_j^s I_{jt}^s + h_j^u I_{jt}^u) \tag{1}$$

$$\text{s.t.} \quad I_{jt}^s = I_{j(t-1)}^s + p_j y_{jt}^p + r_j y_{jt}^r - D_{jt}, \quad \forall j, t > 0 \tag{2}$$

$$I_{jt}^u = I_{j(t-1)}^u + R_{jt} - r_j y_{jt}^r, \quad \forall j, t > 0 \tag{3}$$

$$\sum_{j=1}^{J}(y_{jt}^p + y_{jt}^r) \leq 1, \quad \forall t > 0 \tag{4}$$

$$z_{jt}^p = y_{jt}^p - y_{j(t-1)}^p, \quad \forall j, t > 0 \tag{5}$$

$$z_{jt}^r = y_{jt}^r - y_{j(t-1)}^r, \quad \forall j, t > 0 \tag{6}$$

$$I_{j0}^s = I_{j0}^u = y_{j0}^p = y_{j0}^r = 0, \quad \forall j \tag{7}$$

$$I_{jt}^s, I_{jt}^u \geq 0, \quad \forall j, t \tag{8}$$

$$y_{jt}^p, y_{jt}^r, z_{jt}^p, z_{jt}^r \in \{0, 1\}, \quad \forall j, t \tag{9}$$

The objective function (1) minimizes the sum of setup and inventory holding costs. Constraints (2) and (3) are the inventory balance equations for serviceable and used products, respectively. Constraints (4) establish that: i) only one product can be produced or remanufactured in certain period; ii) production and remanufacturing can not be carried out in the same period. Constraints (5) and (6) are for establishing the production and remanufacturing setup cost incurred when there is product changeover, respectively. The constraints (7) mean that the initial inventory level for all products is assumed zero and that the system is initially idle. Finally, (8) and (9) are the domain constraints for the decision variables.

3 Numerical experimentation

In this section we provide the results and the analysis of the numerical experiments carried out to evaluate the mathematical model suggested for the DLSR. Specifically, we are interested in compare the efficiency in both costs and solving time for the problem with and without returns, i.e, the DLSR and the DLSP. We note that the MILP of Section 2 in which the parameters, variables and specific constraints related to returns are removed, corresponds to the formulation of the DLSP.

To facilitate the understanding of the results and to make a more effective comparison, we consider for the experiments the case of a single product ($j = 1$).

3.1 Experiments design

The instances were generated based on the benchmark set introduced in [22] and [18] for the ELSR, also used in [2], [19], [13] and [14]. All them have a

planning horizon T of 22 periods (workdays of a month). Demand values D_{1t} were generated according to a normal distribution with mean 100 and 20% of coefficient variation. Returns R_{1t} were also generated using a normal distribution with means 50, 70 and 100, and 20% of coefficient variation. The setup cost of production K_1^p is set to 2000 and the setup cost of remanufacturing K_1^r can be 200, 500 and 2000. The unit cost for holding inventory of serviceable products h_1^s is set to 1 and for used products h_1^u can be 0.2, 0.5 and 0.8. Production speed p_1 is set to 200 units per period, and the remanufacturing speed r_1 can take values on 200, 300 and 400 units per period. Note that, as is to be expected in practice, it is assumed that remanufacturing costs are at most equal to production costs and that remanufacturing speed is at least equal to production speed. We generate 10 instances for each on of the 3^4 configurations, that is 810 instances in total. In addition, to evaluate the solving time, we generate one instance for each configuration, with planning horizons of 22, 44, 66, 88, 110 and 132 periods, that is $81 \times 6 = 486$ instances in total.

The model was coded in AMPL and solved for all the instances of above with CPLEX 12.9.0.0 with a time limit of 1800 seconds, on a PC with 8 CPUs Intel Core i7-6700 3.40GHz, 64-bit, 24GB of RAM and CentOS Linux 7.

3.2 Analysis of results for instances with $T = 22$

Next, we present and analyze the results obtained for the instances with a planning horizon of $T = 22$ periods. The values shown in Table 1 are the average cost, the standard deviation and maximum cost of the optimal solutions obtained with CPLEX for the DLSR and DLSP. We decided not to report the runtimes, since they were very low for both problems, less than half a second for all the 810 instances. In the first row of the table, labeled as *"All instances"*, we show the average cost considering all the instances, which is 12480.1 for the DLSR and 10828.9 for the DLSP. This represents around of 15% increase in the costs for the DLSR in average. However, we can note that in the cases of low-cost returns ($K_1^r = 200$ or $h_1^u = 0.2$), the costs are in average a little more favorable for the DLSR. The average costs of these cases are highlighted in the table (underlined and in bold). In fact, for each one of the 90 instances with $K_1^r = 200$ and $h_1^u = 0.2$, we want to remark that the cost of the DLSR optimal solutions is lower than the cost of the DLSP optimal solutions, even reaching differences of more than 35% in favor of the DLSR. We also note that the total number of instances for which the cost is favorable for the DLSR is 255, that is 30% of the total instances. On the other hand, we note that the maximum gap between the average costs of the DLSR and DLSP is for the cases of high-cost returns ($K_1^r = 2000$ and/or $h_1^u = 0.8$).

In the cases of variations on the average quantity of returns (R_{1t}), we note that they do not have a significant impact on the cost gaps. However, we note a favorable trend to the DLSR as the amount of returns increase, as it can be noted for the case of large returns ($R_{1t} = 100$). The opposite behaviour can be observed for the remanufacturing speed (three last rows of Table 1): as the remanufacturing speed increases, also do the average cost gap between DLSR and

DLSP. Therefore, it would be more economically convenient to consider similar speeds for production and remanufacturing, although in fact the remanufacturing speed could be higher, as it often requires less labor effort, materials, and energy.

In Table 1, the higher standard deviation and maximum values obtained for the DLSR compared to the DLSP, may be due to the fact that the variations are in the parameters related to the returns, which do not affect the DLSP. However, this appreciable dispersion in the costs of the DLSR optimal solutions observed for all the instances, would show that the variation in the parameter values has a significant impact on the efficient resolution of the problem.

Table 1. Summary of results for the 810 instances with $T = 22$ for DLSR and DLSP. The columns represent the average, standard deviation and maximum value of the optimal solutions obtained with CPLEX.

		Average		***Stand. desv.***		***Maximum***	
		DLSR	**DLSP**	**DLSR**	**DLSP**	**DLSR**	**DLSP**
All instances		12480.1	10828.9	2858.7	413.6	21086.2	12065.0
R_{1t}	**50**	12653.5	10837.5	2206.8	402.9	18098.0	12065.0
	70	12625.5	10841.8	2671.6	438.0	19351.6	11930.0
	100	12161.3	10807.3	3523.8	399.4	21086.2	12007.0
K_1^r	**200**	**10447.5**	**10834.4**	1890.4	407.0	14865.8	12065.0
	500	11553.2	10816.9	1712.9	413.3	15839.8	11868.0
	2000	15439.6	10835.3	2066.4	421.6	21086.2	12007.0
h_1^u	**0.2**	**10600.6**	**10804.5**	2116.3	393.0	15177.6	11794.0
	0.5	12582.6	10850.2	2483.1	442.9	17746.0	12065.0
	0.8	14257.1	10831.9	2684.7	403.4	21086.2	11930.0
r_1	**200**	11519.7	10846.1	2672.3	419.6	17711.6	12065.0
	300	12610.2	10819.1	2825.5	433.9	20403.2	12007.0
	400	13310.3	10821.5	2796.2	386.9	21086.2	11930.0

The cases in which the DLSR obtained lower costs than DLSP, that is, $K_1^r = 200$ and $h_1^u = 0.2$, are presented in more detail in Tables 2 and 3, respectively.

Table 2 shows the average cost of the optimal solutions for the DLSR and DLSP for the instances with $K_1^r = 200$. The rest of the parameters (R_{1t}, h_1^u and r_1) vary as described in Section 3.1. In column "Gap" we report the difference in percentage between the average costs of the optimal solutions determined as: $100 \times (DLSR\_cost - DLSP\_cost)/DLSP\_cost$). From Table 2 we first note that the DLSR average costs are lower than DLSP in most cases (negative values in the Gap column). In terms of R_{1t}, it can be seen that as the value of returns increases, the cost of the DLSR optimal solutions decreases, reaching a percentage gap near to -14%. For the cases of h_1^u, we note that the sensitivity of the DLSR is significant with respect to this parameter, since the cost gaps vary from -19.3% ($h_1^u = 0.2$) to 11.3% ($h_1^u = 0.8$). Regarding the remanufacturing speed r_1, the analysis is similar to the cases of h_1^u: the cost of the DLSR is very sensitive and increases as the value of r_1 increases, as we mentioned at the beginning of this subsection for the analysis of the results presented in Table 1. In addition,

Table 2. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $K_1^r = 200$.

			DLSR	DLSP	Gap
$K_1^r = 200$	R_{1t}	**50**	11217.9	10789.1	4.0%
		70	10778.4	10877.5	-0.9%
		100	9346.2	10836.6	-13.8%
	h_1^u	**0.2**	8736.0	10831.8	-19.3%
		0.5	10520.5	10816.1	-2.7%
		0.8	12086.0	10855.3	11.3%
	r_1	**200**	9415.7	10881.8	-13.5%
		300	10527.7	10810.3	-2.6%
		400	11399.1	10811.1	5.4%

we observe that the costs are significantly favorable for the DLSR in the case in which the production and remanufacturing speed are the same ($p_1 = r_1 = 200$).

Table 3. Comparison of the average costs of the DLSR and DLSP optimal solutions for the case $h_1^u = 0.2$.

			DLSR	DLSP	Gap
$h_1^u = 0.2$	R_{1t}	**50**	10938.7	10812.1	1.2%
		70	10636.5	10856.8	-2.0%
		100	10226.5	10744.7	-4.8%
	K_1^r	**200**	8736.0	10831.8	-19.3%
		500	9862.4	10808.2	-8.8%
		2000	13203.3	10773.7	22.6%
	r_1	**200**	9881.1	10833.5	-8.8%
		300	10740.5	10801.3	-0.6%
		400	11180.1	10778.9	3.7%

Table 3 shows the results for the instances with $h_1^u = 0.2$. The meaning of the columns is the same as in Table 2. From Table 3 we can note that there are more instances in which the costs of the DLSR is lower than the costs of the DLSP (negative values in column "Gap"). The effect observed for the returns cases R_{1t} is similar to that seen in Table 2, but less marked: as returns amounts increase, the cost of the DLSR decreases. A high sensitivity for the costs of the DLSR optimal solutions is observed against different values of K_1^r, with a percentage gap from -19.3% for $K_1^r = 200$ to 22.6% for $K_1^r = 2000$. For the cases of the remanufacturing speed (r_1), the results are also similar for that observed in Table 2, but, once again, not so marked.

3.3 Analysis of results for large instances

We present in this subsection the results of the experiments carried out to evaluate the computational effort required to solve the problems DLSR and DLSP.

In Table 4 we present the runtimes in seconds for each problem, along with the number of times that the time limit of 1800 seconds, established to CPLEX, is attained. In Figure 1 we show the CPU times required by CPLEX for solving the problems for the different values of T under consideration, represented on a logarithmic scale. As it can be seen in Table 4 and Figure 1, DLSR is considerably more computationally expensive than DLSP. While the CPU times for the DLSP are around 1 second (even for the larger case of $T = 132$), in the case of the DLSR, they grow suddenly (more than 500 seconds for $T = 132$). This is evidenced by the number of times that the time limit of execution is reached by CPLEX for the DLSR, which begins to increase in larger instances. On the other hand, for the DLSP the time limit is never attained.

Table 4. Average runtimes (in seconds) and number of times that the execution time limit is reached by CPLEX to solve the problems DLSR and DLSP for the different values of T considered.

	DLSR		**DLSP**	
T	**Runtime**	**#Tim.lim.**	**Runtime**	**#Tim.lim.**
22	0.07	0	0.006	0
44	0.53	0	0.10	0
66	9.02	0	0.26	0
88	134.03	4	0.82	0
110	362.44	13	1.11	0
132	513.67	19	1.34	0

Finally, we note that the cost gaps for the large instances show, on average, the same behaviour as that observed for the 810 instances with $T = 22$ periods, that is, around a 15% increase for the DLSR compared to the DLSP.

4 Conclusions

In this paper we have tackled an extension of the discrete lot-sizing and scheduling problem in which the demand requirements of products can be also satisfied by remanufacturing used products returned to the origin. We refer to this problem as the discrete lot-sizing and scheduling problem with remanufacturing (DLSR). Remanufacturing can be considered as a key element of the Circular Economy, a paradigm that has emerged to counteract the negative effect on the environment of the traditional linear production of produce, use and dispose.

We provide a MILP formulation for the problem and analyze the results of a numerical experimentation carried out for the case of a single product, with the aim to compare the efficiency in both costs and solving time of the DLSR against the DLSP (the traditional problem without returns). From the numerical experiments conducted, we conclude that the problem extension with recovery options can offer economic benefits in the case of low-cost returns and, to a lesser extent, for those cases in which the number of returns is relatively high compared

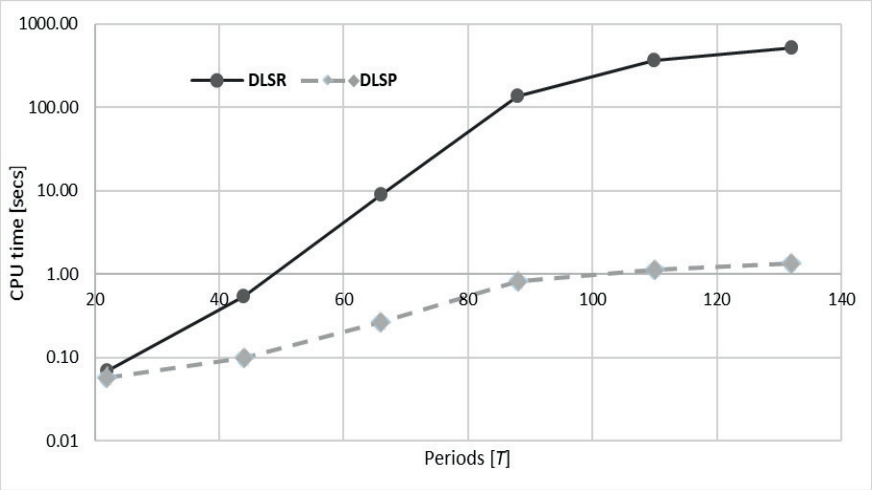

Fig. 1. CPU times in average required by CPLEX to solve the problems DLSR and DLSP for the different values of T. The CPU time is expressed in logarithmic scale in seconds.

to the demand requirements. In addition, we note that similar production and remanufacturing speeds appear to be a more favorable configuration, even in those cases with large returns. In terms of solving times, we show that the DLSR is much harder to solve than the DLSP, in particular, as the size of the instances increases. Thus, we conjecture that the DLSR belongs to the complexity class of NP-hard problems.

Taking into account the results of the numerical experimentation summarized above, future research on DLSR should involve the development of efficient and effective solving procedures for the problem, possibly extending those suggested for the DLSP or ELSR. Another interesting topic to address is the analysis of the order of complexity of the problem. This analysis should involve not only the general case, but also particular cases such as the case of a single product as in [24] for the DLSP, or the case of sufficient returns at the first period as in [15] and [16] for ELSR. It would be also interesting to study the DLSR with more than one machine or processing line. In particular, the case in which production and remanufacturing are allowed in the same period. Considering the environmental side of the problem, it would be interesting to investigate the returns usage rate in the optimal or high quality solutions. Also including more realistic assumptions, such as the non-uniform condition of the returns (heterogeneous quality), may be an interesting extension to consider for the problem tackled here.

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Planificación de minutas alimentarias para el casino central de una Universidad Pública de Chile: Un enfoque para la reducción de la huella de carbono

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Abstract. El calentamiento global ha tenido impactos negativos en la calidad de vida, la eficiencia de diferentes sectores productivos y el medioambiente. Los principales responsables de este calentamiento global son los gases de efecto invernadero (GEIs), en particular el diéoxido de carbono (CO_2). Por otra lado, la malnutrición es un tema complejo a nivel mundial, alcanzando alrededor del 60% de la población. Este trabajo aborda ambos problemas mediante el planteamiento de un modelo matemático para planificar las minutas alimentarias de un casino de una Universidad Pública de Chile, satisfaciendo requerimientos de calorías, cantidad de raciones diarias y de diversidad de preparaciones; minimizando la generación de dióxido de carbono equivalente (CO_2 eq). Los resultados muestran que una minuta generada por el modelo propuesto permite una disminución de un 96,85% en las emisiones generadas en comparación con aquellas planificadas habitualmente para un periodo base de 25 días. Se concluye que este modelo podría ayudar a generar minutas diarias alimentariamente saludables y ecológicamente amigables.

Keywords: Planificación, Minuta, Huella de Carbono, Calorías, Modelo de optimización

1 Introducción

En la actualidad, los efectos del calentamiento global se han visto reflejados en la escasez hídrica [11], alteraciones en el ciclo hidrológico, derretimiento de glaciares [8], disminución de la producción agrícola y la calidad de los cultivos [5], disminución de la biodiversidad de ecosistemas marinos [10], impactos negativos en la salud [9], entre muchos otros. Los principales responsables de este calentamiento global son los gases de efecto invernadero (GEIs) en particular el dióxido de carbono (CO_2), GEI de larga duración proveniente de actividades humanas [13].

Por otra lado, la malnutrición es un tema complejo a nivel mundial. En el año 2016, un 39% de las personas de 18 años o más tenía sobrepeso y un 13%

sufría de obesidad [6]. En el otro extremo, se encuentra la carencia en la ingesta de energía y/o nutrientes, representada por el 10,8% de la población mundial en el año 2017 [12]. A todo lo anterior, se suma que más de dos mil millones de personas del mundo no consumen los micronutrientes necesarios, es decir, padecen de "hambre oculta" [7].

Nuestra Contribución: Este trabajo aborda ambos problemas: satisfacer los requerimientos alimenticios y minimizar la generación de GEIs. Específicamente, este trabajo propone un modelo matemático que permita planificar las minutas alimentarias para el casino central de una Universidad Pública de Chile, que satisfaga los requerimientos de calorías, cantidad de raciones diarias y de diversidad de las preparaciones; minimizando la generación de dióxido de carbono equivalente (CO_2 eq).

2 Descripción del problema

En la Universidad Pública bajo estudio, una entidad especializada es la que diariamente planifica las minutas alimentarias que ofrece el casino central a toda la comunidad. Formalmente, la entidad planifica la minuta para un conjunto de días hábiles $\mathcal{D}$ que componen 5 semanas, donde $\mathcal{D}_b$ denotan el conjunto de los días de b-esima semana ($b = 1, \ldots$), i.e $\mathcal{D} = \bigcup_{b=1}^{5} \mathcal{D}_b$.

Esta entidad especializada considera un conjunto de preparaciones $\mathcal{A}$, el cual es definido por la unión de tres subconjuntos disjuntos definidos por un conjunto platos de fondo $\mathcal{A}_I$, un conjunto de postres $\mathcal{A}_J$ y un conjunto de entrada $\mathcal{A}_K$. Una *minuta* para un dia $d \in \mathcal{D}$ corresponde a una tripleta de tres preparaciones: plato de fondo $i \in \mathcal{A}_I$, postre $j \in \mathcal{A}_J$ y entrada $k \in \mathcal{A}_K$. Sea $\mathcal{W}$ el conjunto total de alimentos considerados por las preparaciones. Cada preparación $a \in \mathcal{A}$ es elaborada a partir del conjunto de alimentos, donde la cantidad de cada alimento $w \in \mathcal{W}$ es denotado por $F_{w,a}$. Asimismo, cada preparación $a \in \mathcal{A}$ posee C_a calorías y para cada día $d \in \mathcal{D}$, se debe satisfacer un rango de calorías entre $\underline{Cal}$ y $\overline{Cal}$ junto a una cantidad de raciones del día N_d.

Por política de diversidad de las preparaciones, los platos de fondo y las entradas no pueden repetirse durante el periodo de planificación, mientras que los postres no pueden repetirse en la semana.

Sea E_w la emisión de CO_2 eq por la producción del alimento $w \in \mathcal{W}$. El problema abordado en este artículo es planificar las minutas para los días hábiles, seleccionando un subconjunto de preparaciones, que minimice la cantidad total de emisión de CO_2 eq provenientes de los alimentos utilizados por las preparaciones seleccionadas, respetando los rangos de calorias, cantidad de alimentos y diversidad de preparaciones.

3 Modelo Matemático

Sea $x_{a,d}$ una variable binaria que toma el valor 1 si la preparación $a \in \mathcal{A}$ se entrega el día $d \in \mathcal{D}$, cero en otro caso.

3.1 Función Objetivo

$$[\text{MIN}] \sum_{d} \sum_{w} \sum_{a} F_{w,a} \cdot E_w \cdot x_{a,d} \cdot N_d \tag{1}$$

3.2 Restricciones

$$\sum_{d} x_{i,d} \leq 1 \quad \forall \quad i \in \mathcal{A}_I \tag{2}$$

$$\sum_{d} x_{k,d} \leq 1 \quad \forall \quad k \in \mathcal{A}_K \tag{3}$$

$$\sum_{d \in \mathcal{D}_b} x_{a,d} \leq 1 \quad \forall a \in \mathcal{A}_J; b = 1,2,3,4,5 \tag{4}$$

$$\underline{Cal} \leq \sum_{a} C_a \cdot x_{a,d} \leq \overline{Cal} \quad \forall d \in \mathcal{D} \tag{5}$$

$$\sum_{a \in \mathcal{A}_s} x_{a,d} = 1 \quad \forall s = I, J, K; d \in \mathcal{D} \tag{6}$$

La expresion (1) describe la función objetivo del modelo y cuantifica el total de emisiones de CO_2 de los alimentos asociados a las minutas. El conjunto de restricción (2) y (3) indica que las preparaciones de plato de fondo y entrada no pueden ser repetidas durante el periodo de estudio, de igual manera, el conjunto de restricciones (4) limita la frecuencia de repetición de los postres a una semana. El conjunto de ecuaciones (5) restringe la cantidad de calorías de la minuta diaria. El conjunto de restricciones (6) condiciona la planificación diaria, de modo que sólo se puede elegir una preparación de plato de fondo, postre y entrada cada día.

Los datos obtenidos para la definición de parámetros desde la unidad especilizada fueron las cantidades de raciones diarias, las calorias máximas $\overline{Cal} = 690$ y calorias mínimas $\underline{Cal} = 450$, además de las preparaciones descritas por $|\mathcal{A}_I|$=76 platos de fondo, $|\mathcal{A}_J|$=31 postres y $|\mathcal{A}_K|$=44 entradas, las cuales se combinan para crear la minuta diaria. Las emisiones de CO_2 eq son obtenidas de estudios de Análisis de Ciclo de Vida (LCA) de la literatura ([4], [1], [2]) y de la calculadora ecológica chilena EcoBase [3].El modelo matemático fue implementado en GAMS 2.0.54.3 utilizando CPLEX 12 como solver, en un ordenador con un procesador Intel(R) Core(TM) i5-9300H CPU, 2.40GHz y una memoria RAM de 8 GB.

4 Resultados y Conclusiones

Los resultados obtenidos por el modelo entregan una planificación de minutas diarias para el periodo de estudio cuya cantidad total de CO_2 eq alcanza los 2.212,482 kg. Este valor corresponde a una disminución de 96,85% respecto a la minuta desarrollada por la unidad especializada de la Universidad Pública durante el mismo periodo. La Figura 1 muestra el CO_2 eq emitido durante cada día del período de estudio, generada por minuta diaria generada por al unidad especializada de la Universidad Pública y minuta diaria generada por el modelo de opimizaci ón. Las líneas segmentadas de la Figura 1 indican la emisión diaria promedio de cada minuta, siendo representada la minuta real con color azul, mientras que la minuta planificada/optimizada, en color naranjo.

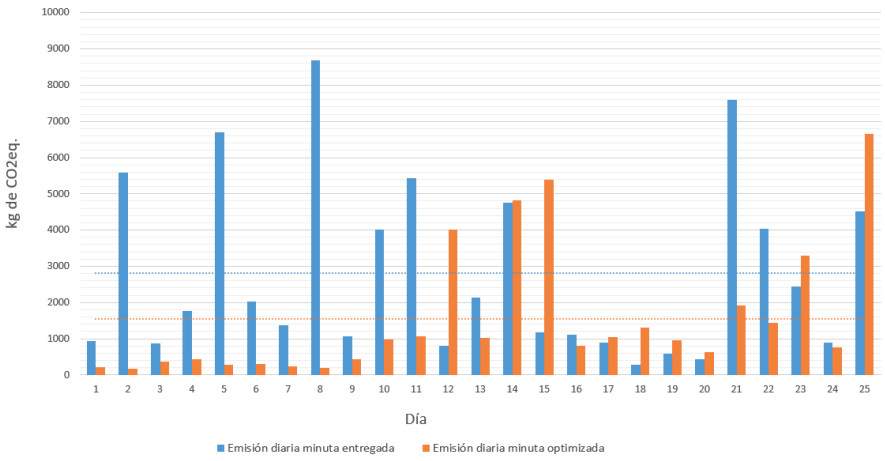

Fig. 1: Emisiones diarias de CO2 eq.

Se concluye que este modelo podría ayudar a generar minutas diarias alimentariamente saludables y ecológicamente amigables. Para trabajos futuros, se recomienda la incorporación de otros factores como los requerimientos de nutrientes y la posible implementación del modelo dentro de una herramienta computacional que sea de fácil uso para el tomador de decisiones.

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lTechnologies investments in the era of digital transformation and sustainable development

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Abstract. The theme Industry 4.0 is a topic that interest is rising in several areas, as it deals with a revolution in the form of production through the introduction of disruptive technologies, which completely changes traditional processes. In parallel, there is great pressure from communities and governments for sustainable development from a social and environmental point of view, this makes companies look for technologies capable of contributing to a sustainable development policy of the organization. The present work aims to analyze articles that aim to investigate the means of investments in clean technologies and environmental innovations, such as estimates of return on investments and their barriers. Through the methodology of a systematic literature review, a bibliographic portfolio was composed of scientific articles. To make research feasible, limited taxes were considered, considering only articles published in the English language, between the years 2000 to 2019 and available in the Web of Science, Scopus, and Science Direct databases.

Keywords: investments, digital technologies, innovation, sustainability, systematic literature review.

1 Introduction

The era of industry 4.0 intrinsically related to advanced production systems, with real-time communication with each other, and also to the possibilities of various data-based analyzes and predictions [1], as well as digital transformation technologies a significant change in the production process [2], brings up the concern about the scarcity of resources pollution, water and air pollution [3], among other forms of environmental degradation. Thus, the current manufacturing models of companies when revealing such

negative social and environmental impacts, stimulated an awakening of awareness on the theme by companies [4].

Ji et al. [5] stated in their study that to contribute to environmental conservation, companies should develop a policy of investing in cleaner technologies, as well as developing better energy efficiency, and creating a sustainable culture. The empirical data from the study by Drohomeretsk et al. [6] has as one of the highlights of their work the practical implication that the use of technologies in equipment can contribute positively to the environmental and economic performance of a company's operations. Machado et al. [7] state that sustainable operations management can be a set of capacities and processes that support business models based on sustainability that have better environmental, social and economic practices as goals. For Böhringer et al. [8] investments in this sense aim to reduce environmental damage, as well as Klassen and Vanchon [9], reiterate that operational investments aim to reduce pollutants in the natural environment. However, these investments are expensive, with longer and riskier payback periods, resulting in limitations for obtaining investments in environmental innovation [10].

Since technologies are means for the sustainable development of corporations, capable of positively impacting the productive processes of companies, often allowing productions to operate in an adaptable and flexible way, or even to have systems for managing waste, processes for reducing or eliminating waste from production methods, among others, but on the other hand, companies have limited resources for investments, or even resist investments in technologies aimed at sustainable development, as they understand that this type of investment may have an uncertain or long-term return, or even ignore the possible benefits that such an investment can provide to the company's operations. With this, the present work aims to investigate through systematic literature review and content analysis, how investments are made in environmental technologies and innovations and what barriers organizations face in this context in the era of digital transformation.

2 Method

The research was carried out using the Proknow-C method (Knowledge Development Process - Constructivist) [11] to compose a portfolio of scientific articles that addressed aspects of the investments, technologies, and sustainability axes.

The Proknow-C method consists of executing several pre-defined steps, as outlined in figure 1, aiming to compose a portfolio with articles of scientific relevance and aligned with the research theme [11].

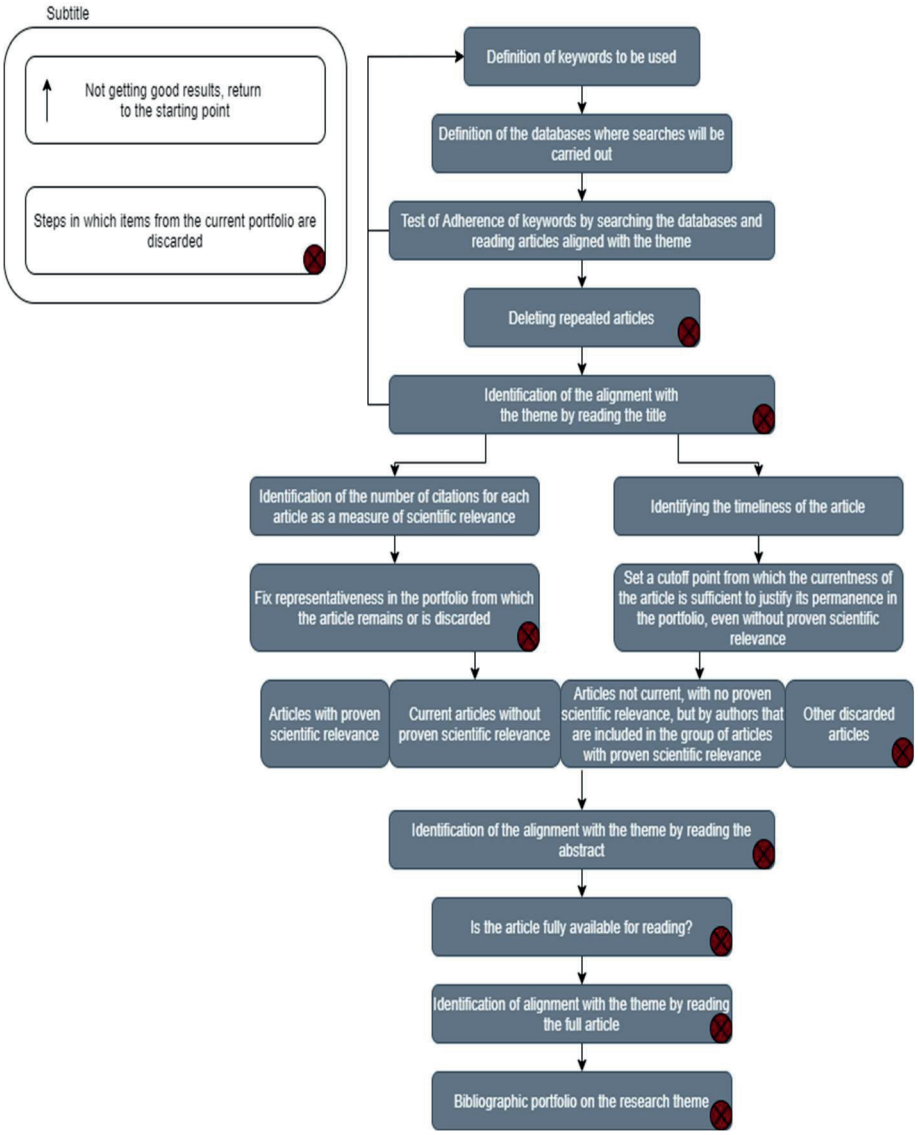

Fig.1 Proknow-C method developed by Ensslin et al. 2010

The first stage of Proknow-C aims to define the research axis and the keywords used in the database search systems, to locate scientific articles by the topic addressed.

The researcher must define the best database to search for articles, if it is not possible to state the best database, the search for scientific articles should be carried out in several databases, since depending on the research area, a database may have greater representation concerning the other, so that if the survey is carried out in several bases,

increase the possibility of locating a larger number of studies that address the research topic.

In this phase, the search expressions in the databases should be imputed, these keywords can be entered individually or combined, and the researcher must also determine limitations regarding the language, period, publication channels and type of bibliographic material, thus allowing research becomes possible.

In the definition of keywords, the researcher must assess whether they are returning articles that are related to the research axis. Therefore, it is suggested that the researcher fully analyze at least two articles, which allows elucidating if the expressions used in the search systems are reflecting articles related to the research.

After this stage of "hunting" scientific articles related to the topic, the researcher will have a raw portfolio, with articles that may or may not be related to the research proposal. Then other filtering processes must be employed to discard articles that do not belong to the scope of the research.

In subsequent steps should be made more filters, which use analysis starting from the titles, abstracts, scientific relevance. This allows obtaining a higher proportion of relevant articles, which have a closer relationship with the research, which, in turn, leads to the provision of a more refined, yet comprehensive portfolio to the point of providing sufficient and essential information to the investigator.

Bearing in mind that the researcher has articles from several databases, there is a possibility that repeated articles have been returned as a result, since a given article may be in multiple bases, so filtering is also necessary for excluding repeated articles.

The next step consists of checking the scientific relevance of the selected articles, in which the researcher should look for the number of times that the articles were cited in other studies. To perform this verification, the tool “Google Scholar” is suggested, in which the title of the article is inserted in the search field of the tool, immediately following the number of times that the researched article was cited, which allows the researcher to evaluate, simply and practically, if the article obtained has proven scientific relevance. However, as suggested by Ensslin et al. (2010) [11], each situation should be assessed individually, given that each research topic has its characteristics, thus being able to present inconsistency both in the number of articles and in the number of citations. Still in this stage in question, the researcher can establish a cut-off number, where he classifies which articles are scientifically recognized and which do not yet have them, and which therefore require further analysis, to decide whether or not to compose the database. Dice. The suggestion of the authors of the method is that the representativeness of scientific articles with confirmed recognition is around 85% concerning the article bank.

In the final phase, the articles established as scientifically significant, are validated by the researcher through reading and analyzing the abstract, which will also allow determining whether the article is in line with the investigated theme, and will remain in the portfolio, or not, and in this case, must then be discarded.

3 Results

From the Systematic Review of Literature performed according to the method described - Proknow-C - the following results were obtained, followed by a brief analysis:

3.1 Portfolio

According to table 1, the keywords were inserted in the Web of Science, Scopus, and Science Direct databases. To limit the search, the searches were restricted to the English language, between the years 2000 to 2019.

Table 1. - Gross Bibliographic Portfolio

Keywords	Data Bases			Total
	Web of Science	Scopus	Science Direct	
(Financing or Investment or feasibility) and (sustainable or sustainability or environmental innovation or carbon emissions or low pollution or prevention control) and (technology or industrial revolution or industry 4.0 or eco-innovation or disruptive innovation or technology)	447	478	999	1924

In the next step, to confirm whether the search terms were in agreement with the investigated subject, 4 related articles were read, and thus it was found that the keywords were significantly appropriate (see table 2).

Table 2. - Articles selected to verify agreement with the investigated subject

References corresponding to selected articles
BOCKEN, N. M. P. Sustainable venture capital - Catalyst for sustainable start-up success? Journal of Cleaner Production, v. 108, p. 647–658, 2015. Ltd.
GHISETTI, C.; MANCINELLI, S.; MAZZANTI, M.; ZOLI, M. Financial barriers, and environmental innovations: evidence from EU manufacturing firms. Climate Policy, v. 17, n. 1, SI, p. S131–S147, 2017.
MUROVEC, N.; ERKER, R. S.; PRODAN, I. Determinants of environmental investments: Testing the structural model. Journal of Cleaner Production, v. 37, p. 265–277, 2012.

SAUNILA, M.; UKKO, J.; RANTALA, T. Sustainability as a driver of green innovation investment and exploitation. Journal of Cleaner Production, v. 179, p. 631–641, 2017.

Then duplicate articles were excluded. Subsequently, the titles and abstracts of the articles were observed, and, in the presence of disagreement with the proposed question, discarded. Thus, only articles according to the research axis, which comprised the review portfolio, were maintained.

The final bibliographic portfolio consisted of 25 articles. According to table 3.

Table 3. - List of articles obtained by applying the Proknow-C methodology:

Portfolio component references
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3.2 Portfolio description

With bibliometric analyzes it was possible to verify that the year 2017 was the year with the highest index, totaling 6 publications, followed by the years 2018 and 2015 with 5 publications each year, with this it is possible to conclude that the interest in understanding the investment movement in technologies and sustainability has been growing in recent years. For Boons and Lüdeke-Freund [12], research on sustainable innovations has been expanding and thus leads us to an understanding that the main way to obtain sustainable societies is through new technologies and social practices.

Just over 32% of the publications in the bibliographic portfolio were made in the Journal of Cleaner Production, which, as stated on the Elsevier website [13], is a journal focused on cleaner, environmental and sustainable research and production practices.

When assessing the number of citations by authors, authors were identified who obtained the scientific relevance of their work, already proven, such as the author's Boons, and Lüdeke-Freund [12] who had their work Business models for sustainable innovation: State-of-the-art and steps towards a research agenda published in the Journal of Cleaner Production cited 1,383 times according to data obtained from the website googles scholar.

3.3 Content analysis

From the bibliographic portfolio, a content analysis was carried out to identify the relationships between the investments, technologies, and sustainability axes and to identify the gaps in studies.

The content analysis consists of a set of methodological techniques that are applied to diversified content so that models can be structured based on the information extracted [14].

Following the methodology of Bardin [14], from the pre-analysis of the material, clippings of the texts were carried out to carry out the categorization in comparable units.

In Fig. 2 it is possible to check the categories and codes created from the bibliographic portfolio and how the articles were classified, presenting an overview of the types of existing investments, how the investments are evaluated and what are the existing barriers regarding investments in technologies and sustainable development.

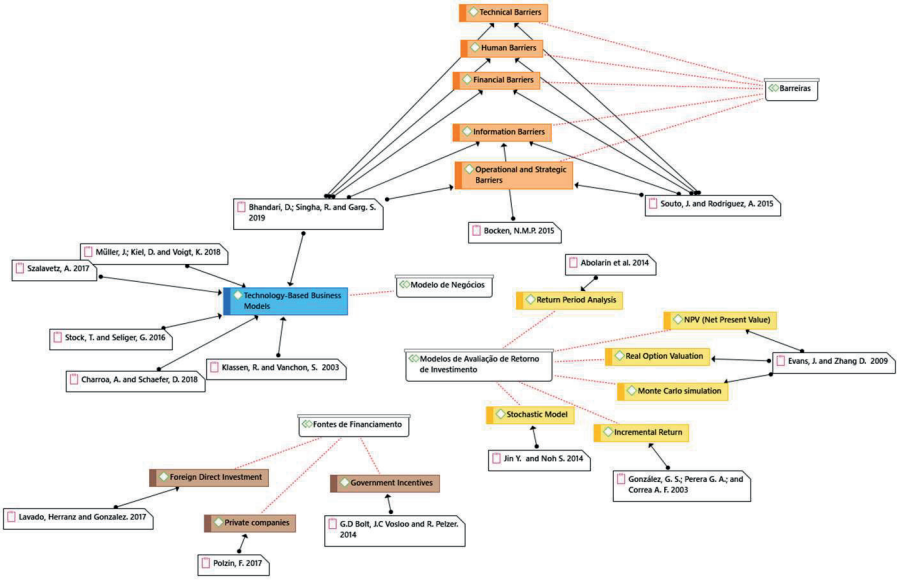

Fig. 2. Categorization and Coding Content Analysis

Day after day, innovations focused on sustainability are gaining more and more attention. As shown in Fig. 3, financing can be made by the public, private companies, and from internal and external sources. According to Polzinz [15], for companies to break through a complex barrier of environmental innovation, it ends up with the help of public institutions through the development of technologies in their institutes and receives contributions from private companies through donations and subsidies.

The 12I is a tax incentive granted by the Republic of South Africa that aims to promote new industrial projects as well as assist in the modernization of existing projects through innovative processes and the acquisition of clean technologies [16].

In the context of small and medium-sized companies, there is a great difficulty in the development of projects and research, this is because these companies usually have limited resources [17], in this sense, according to studies by Melane-Lavado; Herranz; Gonzalez [18], foreign direct financing is a financing stabilizer, because,

when the company does not have access to internal resources, it may have access to external private or public resources.

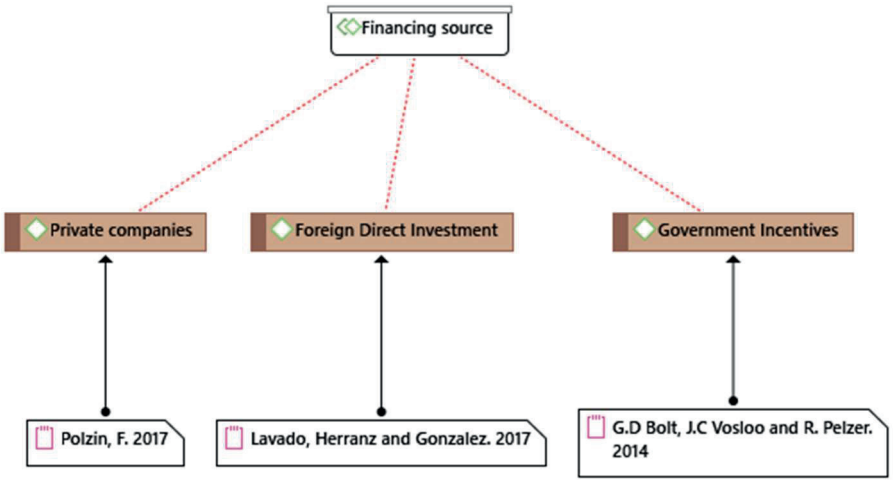

Fig. 3. Financing source.

In the presented business models, it was possible to observe models based on technologies, such as cloud computing [1]environmental technologies in the supply chain [9], clean technologies [19], industry technologies 4.0 [20-21]. For Bhandari; Singh; Garg [19], in addition to being efficient, new technologies develop sustainability from resource consumption, so also says Szalavetz [22] arguing that with the use of advanced manufacturing technologies it is possible to achieve operational excellence, improve the cost-benefit ratio and have a beneficial impact on environmental performance.

González; Perera; Correa [4] state that for decision making on investments related to production, it is necessary to analyze the environmental consequences, however, the traditional financial analyzes do not include environmental impacts, and from this problem, the authors argue that the method of incremental feedback could correct this problem by considering environmental impacts and social benefits in the assessment. Techniques such as ROI (Return on Investment) or the break-even point that are often used, may not provide reliable information [5].

In the context of the automotive industry, considered a highly competitive market and with a growing demand for eco-efficient and sustainable cars, Evans and Zhang [23] state in their study that the real option assessment helps managers understand the administrative and operational flexibility, so that investment-related decision making takes into account, in addition to market conditions, the volatility of the project's value.

The models for evaluating the return on investments considered in the bibliographic portfolio are presented as shown in figure 4.

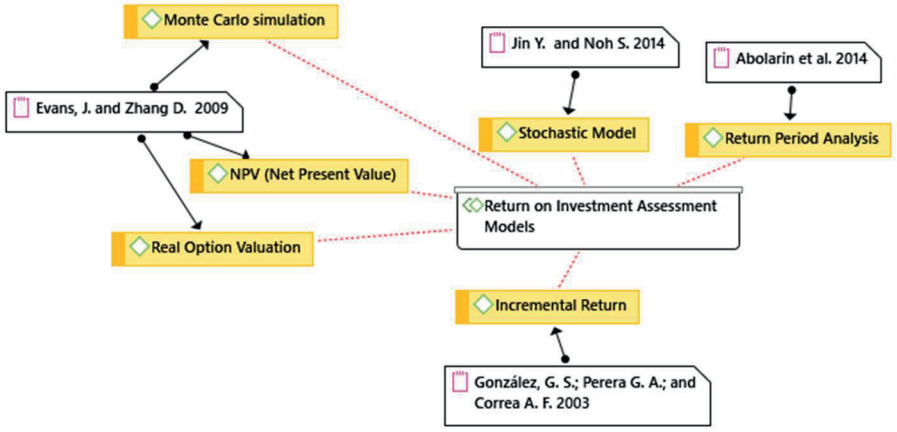

Fig. 4. Investment Evaluation Models.

Since the 1980s, financial barriers have been identified as the main barriers to technological development [24]. Funds and financial institutions that encourage the development of clean technologies are lacking (BHANDARI; SINGHA; GARG, 2019) [19]. Bocken, [25] states that one of the existing barriers to investing in sustainable technologies is the lack of knowledge on sustainability on the part of investors. For Polzin [15], there is a combination of financial, institutional and transition factors that weaken the development of clean technologies, limited access to external sources of finance, the high cost of innovation and the lack of information about the market are factors that limit environmental innovation (SOUTO; RODRIGUEZ, 2015) [26].

Projects that involve sustainable development have the characteristic of having longer terms of return on investment, thus, the investor ends up losing interest in this type of operation, since it seeks to make investments with quick gains (BOCKEN, 2015) [25]. As shown in Figure 5, it was possible to identify numerous barriers faced by organizations to put financial actions into practice within their operations.

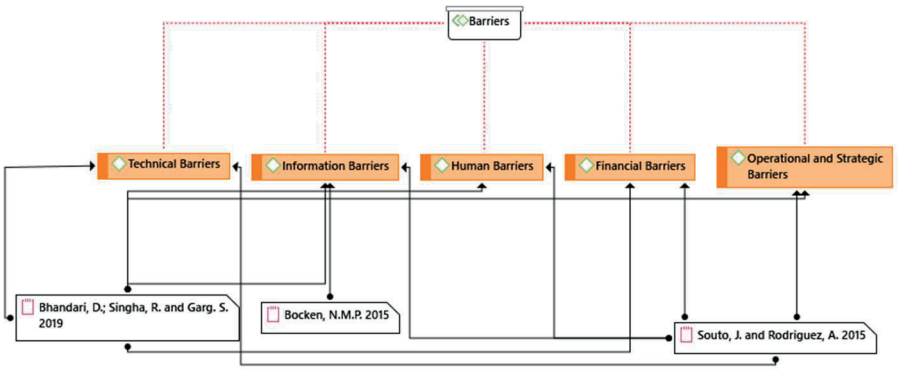

Fig. 5. Barriers to technological innovation in sustainable development.

3.4 Analysis

The development of this research began with the systematic review of the literature, using the Proknow-C method [11]. Based on SLR, a bibliographic portfolio was created, comprising 25 scientific articles related to the areas of investment in cleaner digital transformation and production technologies.

Based on the literature, whether due to legal issues or external pressures, companies are increasingly interested in sustainable development, which ends up having an impact on the academic world, reflecting the interest on the part of researchers to carry out studies on the subject. This trend is perceived in the present study, where the number of publications is increasing year after year.

Many studies are focused on models for evaluating return on investments because investments in environmental innovations and clean technologies are often seen as expensive and long-term investments, which ends up reducing the interest on the part of investors.

Despite the increased interest on the part of organizations in the topic of sustainable development, several authors portray in their studies the barriers to the implementation of sustainable actions in company operations.

A highlight for the financial barrier, that is why 1988 Ashford et al. [24] they already stated that financial barriers are one of the most important groups for the execution of technological changes. In agreement with the statement by Ashford et al. [24], Polzin [15] reiterates that financial and economic barriers are restrictive to innovation in cleaner technologies and technology in general.

4 Conclusion

At a time when technological development is advancing rapidly, with the existence of smart, connected industries and a scenario of increasingly scarce environmental resources, there is an increasing demand from customers and investors for less impacting actions for the environment- environment,

To understand the existing relationships between investments in technologies and sustainability, the present study sought to compose a bibliographic portfolio with articles published from the 2000s until 2019 that dealt with investments in technologies and could make companies sustainable from the point of view. environmental and social views. Therefore, 25 articles were considered in the portfolio, including the article by Boons and Lüdeke-Freund [12] with 1383 citations who have contributed to the development of the literature by demonstrating that sustainable business models and innovations are interrelated in current literature, as well as proposing a normative requirement that business models for innovation should consider. Another point to highlight is the number of publications in the Journal of Cleaner Production, which received 9 publications out of a total of 25 articles. With the content analysis method, it was possible to identify some relationships between the articles, among them the financing of technological innovations with private resources, foreign capital, and public resources through tax exemptions as well as the support of public institutes for the development of technologies.

About investment return valuation models, traditional valuation models and models that consider environmental and social impacts have been identified, such as example of incremental return González, Perera and Correa [4]. In general, the authors argue that traditional validation models are not reliable when it comes to obtaining information on environmental and social results, for them, the models lack real information and that the operations of organizations are reliable.

Finally, several types of barriers to sustainable technological development are pointed out in research, including the barrier of knowledge, information, operational and strategic, technical, human and financial, the latter highlighted, as this is where organizations face the greatest resistance, this why both private and public institutions have low confidence in the return on investments, or why the return periods are long, thus, these institutions choose to make short and medium-term investments.

Finally, this work provided support for an overview of investments in technologies and innovations in the field of sustainability.

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A mathematical model for the cost optimization of bioethanol production integrated into pulp and paper supply chain– The impact of scale and capacity strategies

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Abstract. A mathematical model for the pulp and paper supply chain (P&PSC) network design is presented in this work, where the integration of bioethanol production is evaluated. The optimization model is used to analyze the impact of three cost reduction strategies: economies of scale, transport, and dynamic capacity. The problem is formulated as a generalized disjunctive programming (GDP) model and reformulated as mixed integer linear programming (MILP) one. It is implemented in GAMS and its feasibility has been tested using data from a real case study from Argentina.

Keywords: Pulp and Paper Industry, Bioethanol Production, Supply Chain Integration, Cost Optimization

1 Introduction

Nowadays, the pulp and paper industry is not competitive. The integration of a biorefinery into an existing pulp mill has been determined as a potential pathway for a long-term sustainable growth of pulp and paper industry. Among all the existing possibilities to incorporate biorefineries into P&PSC, this paper deals with the problem of integration of bioethanol production into them [1]. From an Argentinian perspective, the inclusion of biorefineries within the traditional forest industry is of particular interest. In this sense, the problem is presented as an optimization one, formulated by means of a GDP model, which was adapted from a previous work [2]. This contribution analyzes the impact of two cost reduction strategies: economies of scale and dynamic capacity. The aim of this study is to examine the impact of these cost strategies by means of a single comprehensive optimization model.

2 Problem definition and case study

The P&PSC considered in this work involves three echelons: harvesting sites, conversion facilities and consumer regions. Fig. 1 shows the general structure of the

proposed P&PSC and the possible relations among facilities. The P&PSC includes a set of nodes for distributed facilities (nodes *j* and nodes *k* for potential location of pulp mills and paper factory, respectively); and the set of nodes *l* for the integrated ones where different types of plants can be installed.

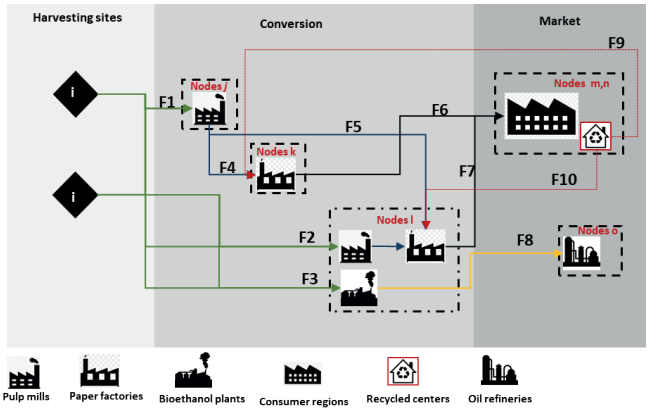

Fig. 1. Generic view on the considered P&PSC, material flow between nodes are represented by solid arrows (direct flow) and dashed arrows (reverse flow).

As in the previous contribution presented by [2], the base scenario (S_0) determines: area of land to harvest; the number, technology, location, and the dynamic capacity profiles of all facilities; and the transportation flows along all P&PSC nodes. In addition, the two cost reduction strategies proposed in this work (see Table 1), involve several modifications both in the mathematical model, and parameters, as well as in the objective function, resulting in optimal design alternatives for the supply chain.

The case study assumes five available harvest areas with two types of raw materials. A total of 14 possible locations for production facilities are assumed. For each plant type, a set of 7 capacities are considered. Five paper consumer's regions are selected, each of them is assigned a recycled paper center. In addition, four largest oil refineries in the country are defined as consumers of bioethanol. Piecewise linearization of transportation cost function through trucks is assumed, costs vary according to the material transported and distance.

Model parameters and some assumptions are determined considering values from the Argentinian forest industry, except the ones related to ethanol production which are taken from the literature. Alternative scenarios (see Table 1), were run to isolate the role of different cost reduction strategies and examine the impact of P&PSC design.

Table 1. Cost reduction strategies

Scenario	Description
S_1	The maximum capacity level is reduced in 27%, to explore the impact of limiting economies of scale.
S_2	Fixed global capacity facility approach is assumed. This scenario is used to explore the impact of introducing dynamic capacity approach.

3 Results and Discussion

The models comprise 42564 constraints, 3560 integer and 19561 positive variables. All instances were implemented in GAMS 24.7.4 with a 2.5 GHz Intel Core i5 processor and solved using CPLEX 12.6.3.0 and took between 50 and 107 CPU seconds to obtain a gap of 0%. Fig. 2 shows the cost breakdown for all scenarios. Table 2 presents of the number and type of plants and the capacity profile for each scenario considered.

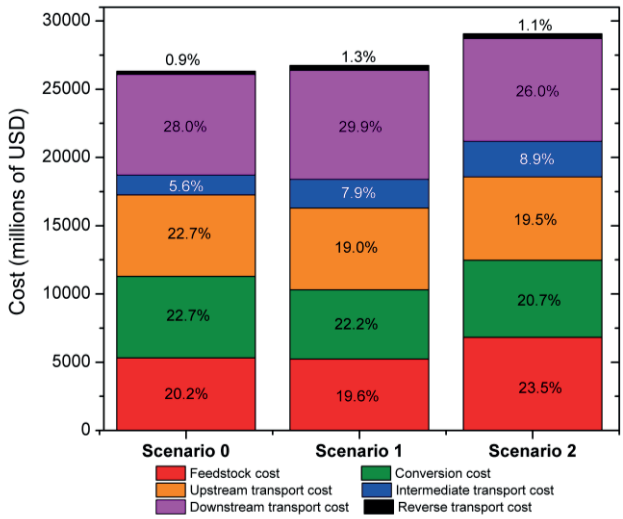

Fig. 2. Optimal cost of P&PSC design for each considered scenarios

Table 2. Number, type of plants and the capacity profile for each scenario considered

			General capacity profile				
Scenario	**Type of facility**	**# of facilities**	**1**	**2**	**3**	**4**	**5**
S_0	Bioethanol	2	20%	20%	39%	39%	100%
	Paper factory	7	41%	48%	48%	56%	100%
	Pulp mill	9	49%	56%	59%	76%	100%
S_1	Bioethanol	1	20%	20%	20%	20%	100%
	Paper factory	8	48%	53%	60%	74%	100%
	Pulp mill	9	43%	58%	66%	87%	100%

	Bioethanol	5	-	-	-	-	-
S_2	Paper factory	10	-	-	-	-	-
	Pulp mill	9	-	-	-	-	-

Large scale versus small scale. Scenario 1 shows a rise in transport cost, the total P&PSC cost is 2% greater than in the baseline case. The increment in the cost of transportation is mainly caused by rising pulp transportation cost and higher recycled paper transportation cost. In addition, similar dynamics of base scenarios are visible in the scenario 1: the benefits of the integration of several forest industries in the same node are used as well as the dominance of economies of scale by selecting large capacity levels. However, unlike the baseline scenario, only one bioethanol facility is located. Moreover, one more paper plant is located in the west of the country, while cellulosic pulp plants are located mainly in the northwest of the country, which explains the increase in the costs of cellulosic pulp transportation (intermediate transport cost) and a greater use and transportation of recycled paper (reverse transport cost).

Fixed versus dynamic capacity allocation. The impact of fixed capacity allocation approach was tested in Scenario 2, which shows a worst supply chain performance in terms of costs, i.e., it is 10% greater than in the baseline case. The best solution suggests the installation of most industries in the first and second year of the planning horizon. Scenario 2 shows a similar dominance of economies of scale but it is characterized by higher overall investment costs (+68%) due to the opening of 6 more facilities compared to the base scenario. Intermediate transport cost for this scenario is 78% higher than the Base scenario for a similar biofuel production level.

4 Conclusions

The proposed model was applied to determine the optimal design of P&PSC considering the bioethanol production. The model involved complex mathematical modeling tasks such as: location and capacity at each node of P&PSC, material flows and interactions among them. In addition, this study evaluated the impact of two strategies to reduce the cost of P&PSC in Argentinian context. Computational results show the model's capability as a decision-making tool for P&PSC design problem. The analysis will be expanded in the future by including the possibility to use harvest residues and facilities byproducts as feedstock as well as considering other industries such as sawmills, medium-density fiberboard and pellets plants among others.

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Relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro

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Resumen. La investigación en temas relacionados con las prácticas de la calidad en cadenas de suministro es una tendencia creciente en los últimos años. Es de particular interés el estudio del impacto de aquellas sobre el desempeño de las cadenas de suministro. Aunque en la literatura se han desarrollado trabajos con modelos o metodologías de análisis sobre esta temática, los aportes continúan siendo escasos. Por ello, en este trabajo se desarrolla un modelo estructural de la relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro. La metodología utilizada se basó en una revisión exhaustiva de trabajos previos para identificar enfoques y variables. En el modelo desarrollado, las prácticas de calidad se representan en cinco variables de entrada: gestión de proveedores, aseguramiento de calidad, gestión del producto, gestión del cliente y administración y gestión.

Palabras clave: Prácticas de calidad, Gestión de cadenas de suministro, Desempeño sostenible.

1 Introducción

El estudio de las prácticas de calidad como un factor de competitividad es una corriente de investigación que amplía el enfoque tradicional de la gestión de cadenas de suministro con respecto a los elementos que tienen impacto en el desempeño global [1] [2]. Según Robinson y Malhotra [3], la gestión de la calidad en cadenas de suministro (*Supply Chain Quality Management – SCQM*) es la coordinación formal e integración de los procesos que involucran a todos los socios en la cadena de suministro para medir, analizar y mejorar continuamente productos, servicios y procesos para crear valor y lograr la satisfacción de los clientes. Para Foster [4], SCQM es un enfoque del desempeño basado en sistemas de mejora que aprovechan las oportunidades creadas por enlaces ascendentes y descendentes con proveedores y clientes.

Por otra parte, y considerando los requerimientos actuales de la medición del desempeño de las organizaciones y sus cadenas de suministro integrando los tres pilares de la sostenibilidad (ambiental, social y financiero) [5], es necesario especificar aún más el

estudio del impacto de la calidad en el desempeño de las cadenas de suministro. Surge así el concepto de gestión sostenible de la calidad en cadenas de suministro (*Sustainable Supply Chain Quality Management – SSCQM*) [6]. Aunque se han desarrollado trabajos sobre teoría y aplicaciones de SSCQM [7], el estudio del impacto de las prácticas de calidad sobre el desempeño de las cadenas de suministro desde un enfoque de sostenibilidad es un tema relativamente nuevo en el ámbito académico que requiere desarrollos desde distintos enfoques conceptuales y prácticos [8].

En los trabajos previos se destaca el desarrollo de un modelo estructural de la relación entre las prácticas de calidad y el desempeño de la cadena de suministro expresado como el rendimiento en la gestión de inventarios, calidad, finanzas y mercado [9]. Igualmente, se ha probado a través de estudios exploratorios que las prácticas de calidad, tales como liderazgo, planeación estratégica, gestión de proveedores, enfoque al cliente, calidad de datos, gestión de procesos y gestión de recursos humanos, son relevantes para el desempeño de las cadenas de suministro [10].

Se ha utilizado el enfoque del análisis multivariado para probar el impacto de las prácticas de SCQM en el desempeño en calidad del producto final [11]. También, se han desarrollado modelos de ecuaciones estructurales del impacto de las prácticas de SCQM sobre el desempeño organizacional [12] y sobre el desempeño en calidad para el cumplimiento de especificaciones y la satisfacción del cliente [13]. En otros modelos se analiza la interrelación a nivel estratégico y operativo entre Justo a Tiempo, gestión de calidad y gestión de cadenas de suministro y se evidencia su impacto conjunto sobre el desempeño organizacional [14].

En los modelos descritos previamente se analiza y prueba el impacto positivo de las prácticas de calidad sobre el desempeño de las empresas y las cadenas de suministro. Sin embargo, el enfoque de medición del desempeño considerado se centra en aspectos financieros, calidad de producto, gestión de inventarios y satisfacción del cliente. No se evidencia en ellos el desempeño sostenible de las cadenas de suministro como la variable respuesta.

Por ello, en este trabajo se desarrolla un modelo estructural que representa la relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro. El modelo propuesto parte del análisis de la literatura de trabajos previos, clasificando los diferentes enfoques respecto a las prácticas de calidad en las cadenas de suministro y se desarrolla una propuesta unificadora con visión integral de la sostenibilidad desde sus tres pilares.

2 Metodología

La metodología utilizada en este trabajo constó de cinco etapas (Fig. 1). En esta sección se describen las tres primeras etapas y, en la siguiente, se muestran los resultados de las etapas cuatro y cinco.

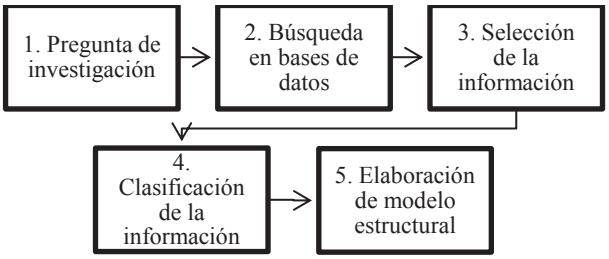

Fig. 1. Etapas de la metodología.

2.1 Pregunta de investigación

El desarrollo del trabajo partió de la formulación de la siguiente pregunta de investigación: ¿Cuáles son las variables que integran un modelo que represente la relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro?

2.2 Búsqueda en bases de datos

La búsqueda de información de trabajos previos se realizó en las bases de datos *Emerald*, *Science Direct*, *Scopus* y *Taylor & Francis*, considerando el periodo de tiempo entre los años 2000 y 2020. Se utilizaron las ecuaciones de búsqueda: "*quality practices*" AND "*sustainable supply chain management*", "*quality practices*" AND "*sustainable supply chain*" AND "*performance*", "*quality management*" AND "*supply chain management*" AND "*performance*".

2.3 Selección de la información

La selección de la información (trabajos previos) se llevó a cabo aplicando los siguientes criterios de inclusión: (i) El documento presenta un modelo o una aplicación de prácticas de calidad en cadena de suministro, y (ii) El documento presenta un aporte sobre el desempeño sostenible de cadenas de suministro. Asimismo, se excluyeron los documentos que: (i) Presentaran modelos o aportes sobre gestión de cadenas de suministro sin considerar las prácticas de calidad, y (ii) Presentaran aportes sobre el desempeño de cadenas de suministro sin considerar los tres pilares de la sostenibilidad.

3 Resultados

3.1 Clasificación de la información

Aplicando los criterios de búsqueda en bases de datos y de inclusión y exclusión descritos previamente, se recuperaron un total de 19 trabajos. Estos fueron analizados con el fin de dar respuesta a la pregunta de investigación planteada y los resultados de la clasificación esquemática se muestran en la Tabla 1. La primera columna corresponde a las variables identificadas (prácticas de calidad en cadenas de suministro), la segunda

columna contiene los descriptores de cada una de las variables y en la tercera columna se muestran los autores relacionados.

Tabla 1. Clasificación de prácticas de calidad en cadenas de suministro.

Práctica de calidad	Descriptores	Autores
Gestión de proveedores	- Integración con proveedores - Gestión de relaciones - Desarrollo de proveedores	[9], [10], [11], [12], [13], [14], [15]
Aseguramiento de calidad	- Protocolos de calidad - Estándares - Calidad de datos e información - Cultura de calidad	[9], [10], [12], [13], [14], [16], [17], [18], [19]
Gestión del producto	- Innovación en el producto - Evaluación comparativa - Gestión de procesos - Diseño del producto - Ciclo de vida del producto	[9], [10], [12], [13], [14], [15], [16], [20], [21], [22], [23]
Gestión del cliente	- Enfoque al cliente - Gestión de relaciones - Satisfacción del cliente	[9], [10], [11], [12], [13], [18], [24], [25]
Administración y gestión	- Planeación estratégica - Gestión financiera - Satisfacción laboral - Gestión de la continuidad - Valores - Capacitación y comunicación	[9], [10], [12], [14], [15], [16], [20], [21], [26], [27]

3.2 Modelo estructural de relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro

Partiendo del análisis de los resultados de la búsqueda en bases de datos condensado en la Tabla 1, se desarrolló un modelo estructural que representa la relación entre las prácticas de calidad y el desempeño sostenible de las cadenas de suministro (Fig. 2). Así, teniendo como base los resultados de la revisión de literatura, se establece que en este modelo las prácticas de calidad comprenden cinco variables de entrada: gestión de proveedores, aseguramiento de calidad, gestión del producto, gestión del cliente y administración y gestión. La variable respuesta corresponde al desempeño sostenible de la cadena de suministro (ambiental, financiero y social).

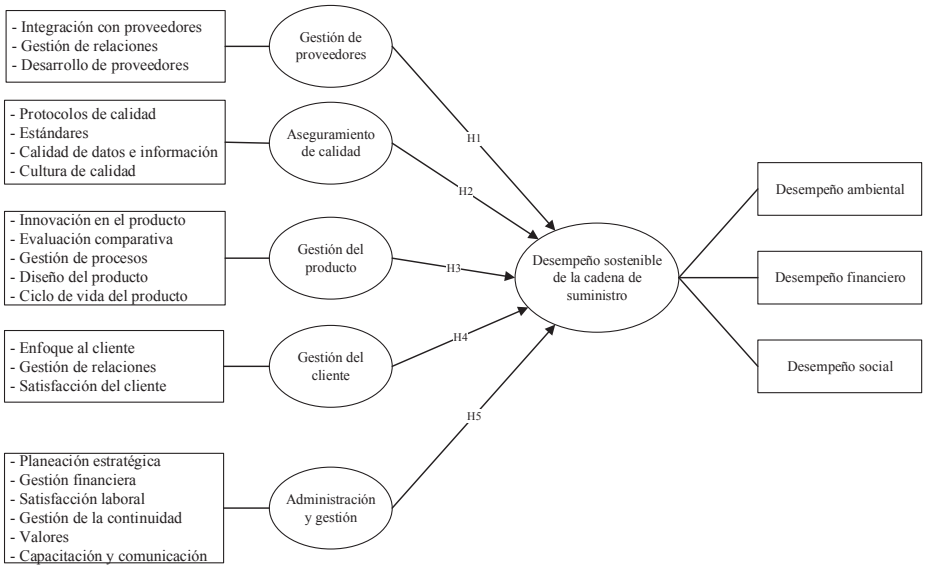

Fig. 2. Modelo estructural de relación entre prácticas de calidad y desempeño sostenible de cadenas de suministro.

Los trabajos previos identificados establecen una relación positiva entre las variables de entrada y la variable respuesta. Así, las hipótesis subyacentes representadas en el modelo son:

H1: La gestión de proveedores tiene un impacto positivo en el desempeño ambiental, financiero y social de la cadena de suministro.

H2: El aseguramiento de calidad tiene un impacto positivo en el desempeño ambiental, financiero y social de la cadena de suministro.

H3: La gestión del producto tiene un impacto positivo en el desempeño ambiental, financiero y social de la cadena de suministro.

H4: La gestión del cliente tiene un impacto positivo en el desempeño ambiental, financiero y social de la cadena de suministro.

H5: La administración y gestión corporativa tiene un impacto positivo en el desempeño ambiental, financiero y social de la cadena de suministro.

La implementación de prácticas de calidad en la gestión de cadenas de suministro genera beneficios para todos los socios [28]. En la medida que las cadenas de suministro analicen y cuantifiquen el impacto de las prácticas de calidad sobre su desempeño global, se contribuye de forma significativa al logro de una producción y consumo

sostenibles [29]. Se requiere del uso de sistemas de medición del desempeño que cuantifiquen en forma balanceada el impacto en los tres pilares de la sostenibilidad.

En el desempeño ambiental se pueden usar indicadores como el porcentaje de producto defectuoso, porcentaje de rechazos y devoluciones, tasa de emisiones, efluentes y residuos, porcentaje de uso de energías renovables [30]. El desempeño social se puede medir a través del nivel de satisfacción de empleados, índice de trabajo decente, satisfacción de partes interesadas, porcentaje de desarrollo de proveedores. El desempeño financiero tiene una mayor práctica y se pueden usar indicadores tradicionales de costo total, costos logísticos, costos de calidad, retorno de la inversión, entre otros [31].

4 Conclusiones

En este trabajo se desarrolló un modelo estructural de la relación entre las prácticas de calidad y el desempeño sostenible de cadenas de suministro, el cual constituye un aporte fundamental al cuerpo de conocimiento del modelado de la gestión de la calidad en cadenas de suministro. En este modelo, las prácticas de calidad se expresan a través de cinco variables de entrada: gestión de proveedores, aseguramiento de calidad, gestión del producto, gestión del cliente y administración y gestión. También, se formularon cinco hipótesis que expresan la relación positiva entre estas variables de entrada y la variable respuesta.

El diseño metodológico utilizado en la búsqueda y selección de trabajos previos a través de criterios de inclusión y exclusión rigurosos permitió seleccionar un conjunto de documentos pertinentes al objeto de estudio en las bases de datos escogidas. Este enfoque de búsqueda sistemática exhaustiva garantiza un proceso centrado en la calidad antes que en la cantidad de fuentes consultadas.

Este trabajo es producto de una línea de investigación en curso en el área de modelado de la gestión de la calidad en cadenas de suministro. Los trabajos futuros se centrarán en el desarrollo de un sistema de ecuaciones estructurales a partir de este modelo y su aplicación en un contexto real. También es de interés integrar técnicas de modelado basado en reglas en una etapa posterior.

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Pesquisa de alternativa de energía eléctrica para la localidad de Fuerte Olimpo Chaco Paraguayo

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Abstract. The Paraguayan Chaco region is in a process of rural electrification, nevertheless, some communities still use power units (generators) for the supply of electricity, while others communities have electricity distribution lines but suffer frequent supply interruptions due to the long distances between the sub-stations and the communities. This is the case of Fuerte Olimpo, which counts with electricity services through a distribution line of 23 kV, which suffers of reliability problems due to its extension of 150 kilometers, and has had 827 hours of electricity supply interruptions in 2019. This study proposes 3 alternatives to operate jointly with the current electricity distribution line: i) with generators, ii) photovoltaic solar energy with battery bank, and iii) through battery banks. The simulation and optimization has been made through the use of HOMER Energy software, in order to determine the most efficient energy source, considering the economic, environmental and technical criteria. The results show that: i) the generators are the most efficient alternative from an economic perspective, with 0,118 USD/kWh of levelized cost of energy (LCOE), but presenting environmental issues. In the other hand, ii) the photovoltaic solar energy has an LCOE of 0,164 USD/kWh, but without greenhouse gases (GHG) emissions. Finally, iii) the mix of electricity distribution line and battery banks has a LCOE of 0,163 USD/kWH and presents null impact to the environment. This study recommends the use of the third alternative as the source of electricity in Fuerte Olimpo, considering the proposed objectives.

Keywords: Renewable energy, isolated localities, COE, HOMER Energy, hybrid system

1 Introducción

1.1 Descripción de la localidad de Fuerte Olimpo – Chaco Paraguayo

El Paraguay cuenta con un superávit de hidroenergía gracias a sus tres centrales hidroeléctricas: ITAIPU Binacional con 14.000 MW de potencia instalada (Paraguay con Brasil), Entidad Binacional YACYRETA con 3.200 MW de potencia instalada (Paraguay con Argentina) y ACARAY propiedad de la Administración Nacional de Electricidad (ANDE), esto conlleva que el Paraguay cuente con una capacidad disponible de 8.810 MW de oferta en su matriz de electricidad; y por otro lado, su demanda máxima en el año 2019 fue de unos 3.550 MW con lo que se puede decir que cuenta con un margen de reserva muy amplio a mediano plazo [1]. El Paraguay cuenta con una alta tasa de acceso a la electricidad 99% de su población, pero existe un paradigma con las

localidades aisladas del sistema interconectado, en su mayoría en el Chaco, como Bahía Negra [2] y Pozo Hondo [3] donde el suministro de energía eléctrica es por medio de centrales térmicas y, por otro lado la localidad de Fuerte Olimpo, la cual se encuentra en condiciones particulares de suministro como se expresa a continuación.

La localidad de Fuerte Olimpo es la capital del departamento de Alto Paraguay. Se encuentra ubicado en el norte del país a orillas del río Paraguay. Dista a 760 km de Asunción. La ciudad está situada en el extremo este del Chaco sobre la margen derecha del río Paraguay y al frente de ella esta Brasil. Cuenta con 5.200 habitantes y su principal actividad socio-económica es la ganadería vacuna y gracias al río Paraguay y sus afluentes, son ricos en la pesca [4].

La localidad cuenta con 1.315 usuarios del servicio de electricidad proveídos por la ANDE y según registros la energía facturada en el año 2019 fue de 16 GWh y esto representó unos USD 250 mil [5]. El suministro es posible gracias a una línea de distribución en 23kV desde la ciudad de Vallemí a una distancia de 150 km, esta distancia ya supera la distancia máxima recomendable según la ecuación de Still [6]. Esta situación de trabajar fuera de los limites recomendables de extensión conllevan a que el suministro tenga varias interrupciones en la continuidad del servicio (fuera de servicios en el año), por citar las interrupciones del servicio accidentales fueron de 541 horas (año 2018) y 469 horas (año 2019) y, por otro lado, los fuera de servicio programados fueron de 61 horas (año 2018) y 358 horas (año 2019) respectivamente [5]. Esta situación de incertidumbre en el suministro y continuidad del servicio de electricidad afecta considerablemente al desarrollo de la localidad.

Ante estas condiciones de suministro con creciente horas de interrupción del servicio anuales, surge la necesidad de una alternativa de fuente de energía o mix de generación in situ con la finalidad de reducir al mínimo las horas sin suministro de energía eléctrica para la localidad y, con ello aumentar la confiabilidad en la continuidad para los usuarios que utilizan la electricidad para la refrigeración de sus alimentos y para el comercio en general, entre otros usos.

Es por ello que este trabajo se centra en analizar las alternativas de obtención de energía eléctrica para los momentos de interrupción de la línea de distribución, buscando operar de forma conjunta de modo a desarrollar un mix de generación más eficiente, confiable y continua. Este caso de estudio se vincula con los desafíos que el Estado debe afrontar y se vincula con los Objetivos de Desarrollo Sostenible (ODS), específicamente el ODS 7, que habla de garantizar el acceso a la energía considerando las potenciales fuentes de generación con que cuenta Paraguay.

Es por ello que este trabajo se enfoca en el análisis de fuentes que puedan suministrar energía eléctrica en los momentos críticos o fuera de servicio de la línea de distribución. La finalidad es encontrar un mix entre: i) grupo electrógeno a diesel, ii) energía solar fotovoltaica y iii) grupo de baterías de respaldo; estas alternativas serian analizadas para su funcionamiento con la línea de distribución actual.

2 Métodos

2.1 Modelado de sistemas con HOMER Energy

El Modelo de Optimización Híbrida para Energía Eléctrica Renovable (HOMER), es el software ampliamente utilizado, disponible en su versión de prueba gratuita y fácil de usar. El Laboratorio Nacional de Energía Renovable (NREL) de EE. UU desarrolló HOMER para simular sistemas conectados a la red y fuera de la red. Su algoritmo computacional se basa en el costo del ciclo de vida. Los algoritmos computacionales de optimización y sensibilidad permitieron evaluaciones tecno-económicas rápidas y sólidas de varias opciones de tecnología de energía renovable (RET) al tener en cuenta el costo de las alternativas de RET y la disponibilidad de recursos de energía renovable. Utiliza la demanda de carga, los recursos, los detalles de los componentes (con los costos), las restricciones, el control de sistemas y los datos de emisión como entrada para simular varias configuraciones factibles y clasificadas por el costo actual neto (NPC).

Normalmente, las simulaciones cubren 8.760 horas de un año típico y un análisis de varios años según el caso de estudio. Los posibles resultados de la simulación HOMER son el tamaño óptimo según el Valor Presente Neto (VPN) y el Costo Nivelado de Energía (COE por sus siglas en ingles), entre otras variables de salida [7].

Los datos de entrada que se utilizaron en este análisis son: i) un perfil de carga diario, ii) alternativas de obtención de energía electrica. Estas son detalladas en el apartado siguiente.

2.2 Descripción del sistema

Las alternativas analizadas para la obtención de generación de respaldo para la localidad fueron planteadas como se puede apreciar en la figura 1, cabe resaltar que todas las alternativas analizadas trabajarían de forma conjunta con la línea de distribución actual:

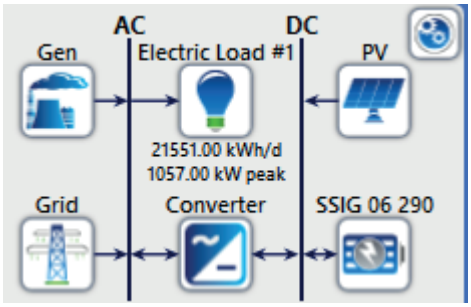

Fig. 1.: Sistema de obtención de energía electrica analizado [1]

[1] Ilustración del esquema de conexión de alternativas de generación, grafico del HOMER Energy

i) Un grupo electrógeno (GE): esta alternativa se considera debido a las condiciones prácticas y de rápida instalación, pero esta alternativa también tiene la desventaja con relación al suministro de combustible, pero esto se puede remediar con unos tanques de reserva (combustible diesel) ubicados estratégicamente a orillas del rio como para su recarga por medio terrestre como por vía fluvial (con el fin de no interrumpir el suministro en temporadas de lluvias donde la localidad se encuentra prácticamente inaccesible por las condiciones precarias de la ruta para su acceso).

ii) Energía solar fotovoltaica (GF): considerando que la radiación en Fuerte Olimpo, datos que fueron importados por el HOMER Energy de la NASA como se muestra en la figura 2. El sistema propuesto estaría compuesto por paneles solares y un banco de baterías de respaldo para los horarios nocturnos y como estabilizadores de potencia en caso de ser necesario.

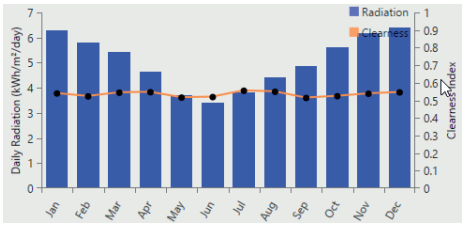

Fig. 2. Radiación solar en Fuerte Olimpo

iii) Banco de baterías (BB): esta alternativa se analiza cómo caso particular consecuente del análisis de energía solar. Esta alternativa considera que el banco de baterías debe operar en conjunto con la línea de distribución y, en caso de una interrupción en el suministro el Banco de Baterías (BB) sería el que suministre energía y posteriormente al restablecimiento de la línea, esta recargaría al Banco de Baterías para el siguiente evento fortuito.

Especificación de sistemas modelados

Las especificaciones técnicas y económicas utilizadas en el análisis con el Homer Energy se presentan en la tabla 1.

Table 1. Especificaciones de alternativas de generación

	Descripción	Especificación
Panel fotovoltaico	Costo de capital (USD/kW) [8]	1.210
	Costo de reemplazo (USD/kW) [8]	1.210
	Costo de mantenimiento y operación (USD/año) [8]	10
	Vida útil	20
Baterías	Costo de capital (USD/kW)[2]	272
	Costo de reemplazo (USD/kW)	272
	Costo de mantenimiento y operación (USD/año)	10
Grupo electrógeno	Costo de capital (USD/kW)[3]	350
	Costo de reemplazo (USD/kW)	350
	Costo de mantenimiento y operación (USD/año) [4]	0,15
	Precio del diesel (USD/litro)	0,796
	Vida útil (horas)	15.000
Línea de distribución 23kV	Costo de capital	No aplica
	Costo de la energía (USD/kWh)	0,0438
	Precio de venta de la energía (USD/kWh)[5]	0,0550

La curva de demanda considerada para la localidad fue proveída por la ANDE [5], y se puede apreciar su comportamiento en la figura 3, ella fue considerada como una curva demanda característica de un día típico (24 horas) que representa a toda la localidad. Para el caso de estudio se tomó un periodo de 10 años y una tasa de descuento del 8% para el VPN.

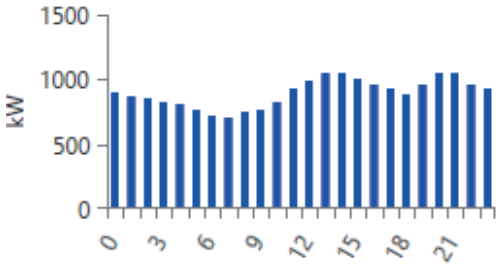

Fig. 3. Curva de demanda característica de Fuerte Olimpo

[2] Los costos de baterías fueron promediados según varias ofertas del mercado en Paraguay.

[3] Los valores de USD/ kW fueron consultados en varios locales y como en Paraguay no hay muchos incentivos para la compra de grupos electrógenos debido a que las tarifas de energía electrica son muy bajos en comparación a la de una energía por medio de grupos electrógenos. El costo para el orden de MW fue proveído por la empresa CATERPILAR

[4] Valor promediado según los estudios en Bahía Negra y Pozo Hondo

[5] La tarifa de venta de energía es un caso particular debido a que los valores son establecidos por el Pliego Tarifario de ANDE (aprobado por decreto del Ejecutivo), donde no se discrimina el lugar de consumo (no hay precios nodales, esto debido al superávit de energía y condiciones particulares del Paraguay)

2.3 Resultados y discusiones

Las alternativas fueron simuladas en el HOMER con los datos de entrada de demanda de energía eléctrica de la localidad y por otro lado los datos técnico-económicos de las alternativas de obtención de energía. Los datos de salida permiten una visión de la alternativa más optima con un enfoque técnico-económico. En la tabla 2 se puede apreciar las condiciones de dimensiones optimas de los generadores con sus correspondiente VPN y COE.

Table 2. Valores de salida del HOMER por alternativas

Alternativa	Descripción	Especificación
Grupo Electrógeno	Potencia (kW)	4.600
	Inversión Inicial (Millones USD)	1,45
	NPC (Millones USD)	12,3
	COE (USD/kWh)	0,116
	Costo de operación (MM USD/año)	1,6
	O&M (MM USD/año)	1,35
	Inversión en combustible (MM USD/año)	0,31
	Combustible diesel (litros)	439,60
	Energía generada (MWh/año)	933
Solar Fotovoltaico + Baterías	Potencia FV (kW)	1.000
	Potencia Conversor (kW)	10.000
	Capacidad del Banco de Baterías (kWh)	70.486
	Inversión Inicial (MM USD)	15,1
	NPC (MM USD)	19,6
	COE (USD/kWh)	0,186
	Costo de operación (MM USD/año)	0,67
	O&M (MM USD/año)	1,23
	Energía generada (MWh/año)	1.378
Grupo de Baterías	Potencia Conversor (kW)	10.000
	Capacidad del Banco de Baterías (kWh)	70.486
	Inversión Inicial (MM USD)	13,9
	NPC (MM USD)	19,3
	COE (USD/kWh)	0,183
	Costo de operación (MM USD/año)	0,809
	O&M (MM USD/año)	1,3
	Energía generada (MWh/año)	727

Según los valores de salida identificados se puede apreciar que entre las alternativas la más ventajosa tomando como indicador el COE sería el Grupo electrógeno con 0,116 USD/kWh, y la menos ventajosa la alternativa de Solar FV y Baterías con 0,186 USD/kWh. Entre todos estos criterios se debería de analizar tanto económica como técnicamente, pero no se debe dejar de lado el criterio ambiental; siendo que en este punto la alternativa de grupo electrógeno se encuentra en desventaja aparte de que se

puede sumar lo referente a la continuidad de suministro de diesel, que también debería ser un criterio válido para analizar. El sistema con energía solar fotovoltaica es comparable en cierto modo a la del mix de la línea con el banco de baterías debido a que ambas evitarían el uso del grupo electrógeno y, a su vez estaría evitando las emisiones de gases de efecto invernadero.

En virtud a la complejidad de la elección de la alternativa que cumpla con los diversos criterios tal como lo expresaron Diemuodeke [7] y Morínigo [3] es necesario un análisis multicriterio considerando varios indicadores, con el cual se puede crear un ranking con las alternativas las cuales cumplan con el objetivo de un mix de generación eficiente, confiable y continua.

3 Conclusión

El Paraguay tiene un gran paradigma con relación a su superávit de energía eléctrica y las localidades aisladas, las cuales no tienen acceso a la energía eléctrica o bien tienen acceso, pero con condiciones de baja confiabilidad lo que incide directamente en la posibilidad de desarrollo económico de las mismas.

Este trabajo realizó un análisis de tres alternativas de obtención de energía eléctrica que trabajarían en conjunto con la línea de distribución para aumentar la confiabilidad y reducir al mínimo posible las interrupciones de la continuidad del servicio de electricidad.

Se identificó que la alternativa del grupo electrógeno es válida técnicamente y en lo económico financiero es la más ventajosa, pero conlleva a efectos colaterales no deseados para el medio ambiente como la emisión de gases de efecto invernadero (de 5.231 Toneladas al año de CO_2).

La otra alternativa fue la de generación solar fotovoltaica la cual es una alternativa ventajosa con relación a la anterior debido a que no tiene emisiones GEI, pero la inversión inicial es elevada y esto conlleva a que el COE sea elevado. Con el fin de reducir la inversión inicial, se analizó el uso de solo un banco de batería para el mix con la línea con lo que se identificaron que los costos son menores y se evita los efectos ambientales no deseados.

El sistema que mejor responde a las necesidades de: i) aumentar la confiabilidad, ii) que su impacto en el medio ambiente sea el menor posible y, iii) que esto represente un costo no tan elevado para el mix; es la de sistema con banco de baterías con un COE de 0,183 USD/kWh. Este valor no es comparable con la tarifa nacional de 0,055 USD/kWh que la ANDE recibe por la energía vendida, pero es una solución que el gobierno debería de plantear con el fin de impulsar el desarrollo económico-social de la localidad considerando su ubicación estratégica como punto de resguardo de la soberanía del Paraguay.

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A Benders Decomposition Approach for an Integrated Bin Allocation and Vehicle Routing Problem in Municipal Waste Management

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Abstract. The municipal solid waste system is a complex reverse logistic chain which comprises several optimisation problems. Although these problems are interdependent – i.e., the solution to one of the problems restricts the solution to the other – they are usually solved sequentially in the related literature because each is usually a computationally complex problem. We address two of the tactical planning problems in this chain by means of a Benders decomposition approach: determining the location and/or capacity of garbage accumulation points, and the design of collection routes for vehicles. We also propose a set of valid inequalities to speed up the resolution process. Our approach manages to solve medium-sized real-world instances in the city of Bahía Blanca, Argentina, showing smaller computing times in comparison to solving a full MIP model.

Keywords: municipal solid waste; reverse supply chain; integrated allocation-routing problem; Benders decomposition algorithm; valid inequalities.

1 Introduction

Regardless of their size, city councils have the duty to provide efficient service to their constituents. Municipal Solid Waste (MSW) management is a crucial example of such a service. It has direct economic and a social impacts; poor collection service can be both expensive and unsanitary. In this paper, we will focus on a less traditional MSW design called Garbage Accumulation Points (GAP). Instead of providing a "door-to-door" pickup of garbage, constituents have to drop their garbage at specific facility – the GAPs. These facilities can range from collective bins to recycling centres. When using GAPs, MSW management comprises the following design decisions:

– The design of a pre-collection network, which consists in defining the location and capacity of GAPs.

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– The design and schedule of routes for collection vehicles.

The geographical distribution of GAPs affects the actual route that the collection vehicles must perform. Additionally, the storage capacity of these sites will define the visit frequency in order to avoid overflow. Finally, the availability and type of vehicles[1] affect the distribution and capacity of the GAPs in a (global) optimal solution. Thus, there is a trade-off between the cost of the installation of GAPs and the routing cost; solving both simultaneously is often beneficial [12]. However, solutions in the literature [7, 10, 20] often address each separately. This is due to the complexity of tackling MSW as a whole. Indeed, only solving the design of routes is tantamount to solving a Vehicle Routing Problem (VRP) [23], a well-known NP-hard problem.

In this paper, we propose the following contributions to the field of MSW management with GAPs:

– A novel mathematical model which combines the allocation of bin arrangements to GAPs and defining collection routes (Section 3.1).
– A Benders decomposition-based approach to tackle the resulting problem (Section 4).

The problem we are tackling is an "inventory routing problem" [4]. The resulting formulation is a mixed-integer program (MIP) which is still too large to be tractable. However, we can see it as a combination of two problems:

1. a routing problem, similar to a vehicle routing problem [23]; and,
2. an allocation problem, similar to a nonlinear resource allocation problem [3] – in which the used amount of resource (bin) should be minimized, though not limited.

This *natural* decomposition lead us to use Benders decomposition [1], a well-suited method for problems with this structure. Benders decomposition works by solving such problems in an iterative fashion. First, it solves the *difficult* part to generate a candidate solutions. It then checks this solution against the dual of the *easy* part. From the dual solution, it either terminates, when the dual solution's objective value is equal to an incumbent; or, it generates constraints, called "Benders cuts," which are added to the difficult part and the problem solved anew.

However, we cannot use standard Benders decomposition because the subproblem contains integer variables. Therefore, we use a framework called Unified branch-and-Benders-cut (UB&BC) [17]. This framework is based on a modified Branch-and-Cut (B&C) with callbacks from a commercial solver. In the callbacks, it derives dual information and an upper bound for the subproblem. Using these, it terminates the branch-and-bound tree with a set of *open solutions* – whose objective function value falls below the best upper bound. To find the global optimum, the B&C is followed by a post-processing phase where the framework solves those open solutions to integer optimality.

[1] Mainly capacity, but could also be cost.

We test our model on a real-world use case: the city of Bahía Blanca, Argentina (Section 6). Although the city currently uses a door-to-door collection service, they are interested in switching to GAPs. We simulated instances using data from a survey [5] and provide optimal allocation and routing for a variety of scenarios. Finally, we present our conclusions and future directions in Section 7.

2 A working example

In this section we will present a short example to illustrate the workings of our solution approach. We will use a toy instance shown in Fig. 1a. It comprises: a two-day-horizon, two GAPs, and two vehicles. We also consider two types of waste bins with a storage capacities of 1.1m^3 and 1.73m^3 respectively.

We will now show the iterations the solution algorithm takes.[2] At each iteration, we will report:

- the master solution (routing cost, which includes GAP allocation per vehicle per day);
- the objective function value of the LP relaxation of the subproblem (lower bound);
- the heuristic value (upper bound); and,
- the total cost of the solution.

A graphical representation of the iterations is provided in Figs. 1b to 1d.

Iteration 1. The first solution uses one vehicles on two days and one vehicle the second day only.

$$v_{0,0} : (0, 2) \to (2, 0)$$
$$v_{0,1} : (0, 2) \to (2, 0)$$
$$v_{1,0} : (0, 1) \to (1, 0)$$

The routing cost is: 494.2. The LP relaxation has an objective function value of 7.96 while the heuristic has a value of 10.48. We add a Benders cut to the master problem and continue.

Iteration 2. The second solution uses two vehicles with different routes during one day:

$$v_0 : (0, 2) \to (2, 0)$$
$$v_1 : (0, 1) \to (1, 0)$$

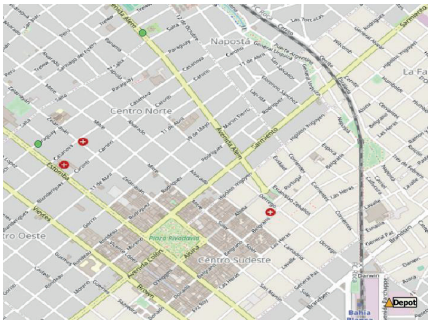
The routing cost is: 381.8. The LP relaxation has an objective function value of 7.06 while the heuristic has a value of 10.48. We add a Benders cut to the master problem and continue.

[2] We use the complete problem (**M1**) augmented with valid inequalities Eqs. (2) to (4). The Benders cuts we generate are "optimality cuts" given by Eq. (8b).

Iteration 3. The third solution found uses a single vehicle with the same route on both days, given by:

$$v_0 : (0, 1) \rightarrow (1, 2) \rightarrow (2, 0)$$

The routing cost is: 316.8. The LP relaxation has an objective function value of 8.58 while the heuristic has a value of 10.48. We add a Benders cut to the master problem and continue.
At this point, the B&C will finish as no improving solution can be found, we can progress to the post-processing.



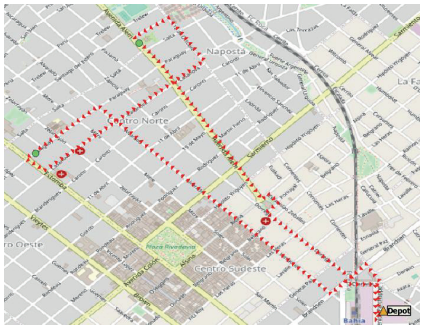
(a) Location of the depot and the two GAPs (green circles) on the toy instance.



(b) It. 1: The first (blue) vehicle uses its route both days, while the second (red) vehicle only operates on the first day.



(c) It. 2: Both vehicles operate during the first day.



(d) It. 3: Only one vehicle operates during one day

Post-processing. At the start of the post-processing phase, the UB&BC orders solutions according to their lower bound values. In this case, it will process the solutions in reverse order: 3, 2, 1.
Starting with the solution found in Iteration 3, we solve the subproblem to integer optimality. This gives an optimal value of 10.48 – the same as the heuristic. Being an integer value, it can be used to update the upper bound to: 347.28 (routing + delivery).

Then, the framework verifies that the remaining open solutions' values are lower that the new-found upper bound. Both solutions found at Iterations 1 and 2 exceed the best upper bound and are thus skipped.

Our approach has managed to find the optimal solution to the problem. It did so as an integrated algorithm which solved the routing and allocation problems at once.

3 A mathematical model of MSW

3.1 Model formulation

The model has the following sets:

- I: the set of potential GAPs.
- $L = \{l_0, l_1, \ldots, l_{|L|}\}$: is an ordered set of vehicles. We consider a homogeneous and finite fleet of vehicles.
- T: the set of days in the time horizon, which coincides with a week (seven days).
- R: the set of possible visit combinations.
- U: the set of all bin arrangements that can be installed in a GAP.

A potential GAP $i \in I$ is a predefined location in an urban area in which bins can be installed. We define the superset: $I^0 = I \cup 0$, where 0 is the depot from which vehicles start and finish their daily tours, and where the collected waste is deposited. We also define a special notation for the set of edges given a set of nodes: $E(\cdot)$, such that: $E(I) = \{\, (i,j) \mid i \in I, j \in I, i \neq j \,\}$. Bin arrangements are set of bins that are feasible to install in a GAP, respecting the space limitation.

We now define the parameters of the model:

- Q: vehicle capacity.
- c_{ig}: travel time between i to g.
- s_i: service time of GAP i.
- b_i: waste generation per day at GAP i.
- cap_u: capacity of bin arrangement u.
- cin_u: adjusted cost of installing bin arrangement u for the time horizon T.
- α: cost per kilometre of transportation.
- β_r: maximum number of days between two consecutive visits of the visit combination r.
- a_{rt}: 1 if day t is included in visit combination r.
- TL: time limit of the working day.

Notice that cin_u is an *adjusted cost*. This is because we are considering two different level of decision and cost:

1. a strategic decision that involves purchasing and installing the bin arrangements that will last probably for several years; and,
2. a tactical decision which involves the transport costs of the routing schedule [19].

Therefore, the cost assigned to a bin arrangement (cin_u) includes a proportional part of the purchase/installation cost and the maintenance cost. With regards to parameters a_{rt} and β_r, they can be introduced with an example:

Example 1. Let time horizon T be a week – i. e., $T = \{t_1, t_2, t_3, t_4, t_5, t_6, t_7\}$. Then, one possible visit combination $r* \in R$ is $\{t_1, t_3, t_5, t_7\}$. In this case, we have: $a_{r*t_1} = a_{r*t_3} = a_{r*t_5} = a_{r*t_7} = 1$, and, conversely: $a_{r*t_2} = a_{r*t_4} = a_{r*t_6} = 0$. Thus, the maximum number of days between two consecutive visits that this combination has is two days: $\beta_{r*} = 2$, and the chosen bin arrangement for this GAP must be able to store the waste generated in two days. (A similar consideration is performed in [12].)

Finally, we define the following decision variables:

- x_{iglt}: binary variable set to 1 if vehicle l performs the collection route between GAPs i and g on day t, 0 otherwise.
- v_{iglt}: continuous variable representing the load of vehicle l along the path between GAP i and g on day t.
- m_{ir}: binary variable set to 1 if visit combination r is assigned to GAP i, 0 otherwise.
- n_{ui}: binary variable set to 1 if bin arrangement $u \in U$ is used for GAP i, 0 otherwise.

We can now present the mathematical model for the MSW management problem:

$$\min \quad \sum_{\substack{i\in I\\ u\in U}} n_{ui}\ cin_u + \alpha \sum_{i,g\in E(I^0)} c_{ig} \left(\sum_{\substack{l\in L\\ t\in T}} x_{iglt} \right) \qquad (\mathbf{M1})$$

$$s.t. \quad \sum_{u\in U} n_{ui}\ cap_u \geq \sum_{r\in R} b_i m_{ir} \beta_r \qquad \forall\ i \in I \quad (1a)$$

$$\sum_{u\in U} n_{ui} = 1 \qquad \forall\ i \in I \quad (1b)$$

$$\sum_{r\in R} m_{ir} = 1 \qquad \forall\ i \in I \quad (1c)$$

$$\sum_{\substack{g\in I^0, g\neq i\\ l\in L}} x_{iglt} - \sum_{r\in R} a_{rt} m_{ir} = 0 \qquad \forall\ t \in T,\ i \in I \quad (1d)$$

$$\sum_{i\in I^0, i\neq q} x_{iqlt} - \sum_{g\in I^0, g\neq q} x_{qglt} = 0 \qquad \forall\ q \in I^0,\ l \in L,\ t \in T \quad (1e)$$

$$\sum_{i\in I} x_{0ilt} \leq 1 \qquad \forall\ l \in L,\ t \in T \quad (1f)$$

$$\sum_{i,g\in E(I^0)} (c_{ig} + s_i)\ x_{iglt} \leq TL \qquad \forall\ l \in L,\ t \in T \quad (1g)$$

$$v_{iglt} \leq Q\ x_{iglt} \qquad \forall\ (i,j) \in E(I^0), l \in L,\ t \in T \quad (1h)$$

$$\sum_{i \in I^0, i \neq g} v_{iglt} + b_g \sum_{r \in R} (m_{gr}\ \beta_r) \leq \sum_{i \in I^0, i \neq g} v_{gilt} + Q \left(1 - \sum_{i \in I^0, i \neq g} x_{iglt}\right) \quad \forall\ g \in I,\ l \in L,\ t \in T \tag{1i}$$

$$v \geq 0; n, x, b \in \mathbb{B}$$

The objective function is the sum of the routing cost and the adjusted cost of installing bins. Equation (1a) limits the maximum amount of garbage that can be accumulated in a GAP to the installed capacity of the bin arrangement. Equation (1b) enforces that one bin arrangement has to be chosen for each GAP. Equation (1c) establishes that one visit combination is assigned to each GAP. Equation (1d) ensures that each GAP is visited by the collection vehicle the days that corresponds to the assigned visit combination. Equation (1e) ensures that if a vehicle visits a GAP, it leaves the GAP on the same day. Equation (1f) states that every vehicle can be used at most once a day. Equation (1g) guarantees that a tour does not last longer than the allowable time limit associated with the working day of the drivers. Equation (1h) limits the total amount of waste collected in a tour to the vehicle capacity. Equation (1i) establishes that the outbound flow after visiting a GAP equals the inbound flow plus the waste collected from that GAP and, thus, also forbids subtours.

3.2 Valid inequalities

The model presented above for the MSW (**M1**) is still a difficult problem. In particular, it contains a lot of *symmetric solutions.* Two solutions are said to be symmetric if they have the same objective function value but different variable assignments. Consider the following: during a given day, two trucks undertaking the same collection route would have the same cost. There is no way for the solver to omit one of them.

One way to address this issue is to add Valid Inequalities (VIs) to the model. A VI is a constraint that reduces the feasible polytope of the problem without removing every optimal solution. We decided to focus on VIs for the routing part of the problem because the allocation part is *easy* in comparison. For examples of VIs in the context of vehicle routing problems, we refer the interested reader to [6].

One thing to remember is that our graph is asymmetric. Therefore, we do not need to address symmetries in routes with the same GAPs. We have developed the following valid inequalities to remove as much symmetry from the optimal solutions as possible.

Empty start. A vehicle must start its tour unloaded. This prevents solutions with different *delivery plans* – when a vehicle finishes its collection tour below full capacity, we can consider another solution where the vehicle starts with any amount less than the difference.

$$v_{0glt} = 0, \forall\ g \in I,\ l \in L,\ t \in T \tag{2}$$

Vehicle ordering. We impose that a vehicle with index l can only leave the depot if the vehicle with index $l-1$ has. In the case where a solution does not use all available vehicles, we can consider swapping an unused vehicle with a used one. For brevity, we define: $L' = L \setminus \{0\}$, as the set of vehicles minus the first one.

$$\sum_{i \in I} x_{0ilt} \leq \sum_{i \in I} x_{0ipt}, \forall\ l \in L',\ p = l-1,\ t \in T \tag{3}$$

Furthest visit. We assign the furthest GAP from the depot to the first vehicle. Because each GAP must be visited at most once a day, so does the furthest. Because only one vehicle can visit each GAP on a given day, we can forbid others vehicle than the first vehicle – using L' defined above – to visit the furthest GAP.

$$\sum_{i \in I, t \in T} x_{iglt} = 0, \forall\ l \in L', g = \underset{i \in I}{\operatorname{argmax}}\, c_{0i} \tag{4}$$

4 A resolution approach based on Benders decomposition

The classic Benders decomposition was devised in [1] for addressing large MIPs that have a characteristic *block diagonal* structure. In summary, it starts by decomposing the *original problem* into a *master problem* and a *subproblem*. The master problem is a relaxation of the original problem used to determine the values of a subset of its variables. It is formed by retaining the *complicating variables*, and projecting out the other variables and replacing them with an *incumbent*. The subproblem is formed around the projected variables and a parameterised version of the complicating variables. By enumerating the extreme points and rays of the subproblem, the algorithm defines the projected costs and the feasibility requirements, respectively, of the complicating variables. Because this enumeration is seldom tractable, the algorithm proceeds in the following manner:

1. It solves the (relaxed) master problem to optimality, which yields a *candidate solution.*
2. This candidate solution is used as a parameter in the subproblem.
3. The resulting problem is solved to optimality and, using LP duality, a set of coefficients are retrieved.
4. These coefficients are used to generate a constraint, called a "Benders cut," which is added to the master problem.
5. If the objective function value of the subproblem is equal to the incumbent value in the master problem, the algorithm stops. Otherwise, it repeats from point 1. using the master problem with the additional constraint.

One key limitation of the classic Benders decomposition is that the subproblem cannot contain integer variables. This is because of point 3. above: the method needs to use LP duality, which is not well-defined for MIPs. We use a recent framework called Unified branch-and-Benders-cut (UB&BC) [18] to bypass this issue. This new framework operates by using a modified B&C where, at each integer node, it:

1. solves the LP relaxation of the subproblem to get a lower bound and generate Benders cuts; and,
2. uses a heuristic to determine if the master solution is feasible and, if yes, a valid, global upper bound.

The second point is key: by maintaining a valid upper bound, the framework ensures that no optimal solution is removed during the search. However, this leads to having a set of *open solutions* after finishing the B&C tree – solutions whose objective function value falls between the lower and upper bound. Thus, the UB&BC finishes by a *post-processing phase* during which subproblems associated with open solutions are solved to integer optimality. The combination of maintaining a global upper bound and using a post-processing phase enables the framework to find an optimal solution.

As stated in Section 3.1, the problem addressed in this work comprises two characteristic decision-making problems in MSW. On the one hand, the allocation of bins in the GAPs and, on the other, the design and schedule of routes for the collection vehicles. This division can be exploited by applying Benders decomposition. The bins allocation equations are moved to the subproblem while the master problem aims at designing the schedule and routes of the collection vehicles.

4.1 Creating the subproblem

The subproblem, which aims at allocating the bins of each GAP, is an integer programming problem:

$$q(\overline{m}) = \min \quad \sum_{\substack{i\in I\\ u\in U}} n_{ui}\ cin_u \qquad (\mathbf{SB})$$

$$s.t. \quad \sum_{u\in U} n_{ui}\ cap_u \geq b_i \sum_{r\in R} \overline{m_{ir}}\ \beta_r \qquad \forall\ i \in I \qquad (5a)$$

$$\sum_{u\in U} n_{ui} = 1 \qquad \forall\ i \in I \qquad (5b)$$

$$n \in \mathbb{B}$$

We define the positive continuous variables δ_i and unrestricted continuous variables γ_i, the dual variables of Eqs. (5a) and (5b) respectively. The dual formulation of the LP relaxation of (**SB**), which will be used to generate cuts, is then:

$$q^{LP}(\overline{m}) = \max \quad \sum_{i\in I}\left(\gamma_i - \delta_i b_i \sum_{r\in R}(\overline{m_{ir}}\beta_r)\right) \qquad (\mathbf{LP})$$

$$s.t. \quad \gamma_i - \delta_i \sum_{u\in U} cap_u \leq \sum_{u\in U} n_{ui} \qquad \forall i \in I \qquad (6a)$$

$$\delta, \gamma \geq 0$$

Heuristic for the subproblem. In order to apply Benders decomposition when the subproblem has integer variables, an efficient method for solving the subproblem is required. Therefore, we devised a rounding heuristic procedure based on the LP relaxation of the subproblem:

1. We solve the LP relaxation of (**SB**). The (relaxed) solution will contain n_{ui} with fractional values.
2. We estimate the *joint fractional capacity* K_i^f of each GAP using:
$$K_i^f = \sum_{u \in U} n_{ui}\ cap_u \tag{7}$$
3. We define a feasible (non-fractional) bin arrangement $u \in U$ for each GAP by finding the bin arrangement with minimal cost among those with storage capacity larger than K_i^f. It is guaranteed that there will always be a bin arrangement which respects this rule since considering Eqs. (5b) and (7) implies that: $K_i^f \leq cap_{u*}, \forall\ i \in I$, where $u* = \text{argmax}_{u \in U}\{cap_u\}$.

4.2 Stating the master problem

The master problem retains the same constraint structure as (**M1**) but the bin allocation part is replaced by an incumbent variable q. Let us consider the set of extreme points ($\mathcal{O}$) and extreme rays ($\mathcal{F}$) of the LP relaxation of (**SB**). These generate the optimality (8b) and feasibility (8a) cuts, respectively. Therefore, the master problem is:

$$\min \quad \alpha \sum_{i,g \in E(I^0)} c_{ig} \left(\sum_{\substack{l \in L \\ t \in T}} x_{iglt} \right) + q \tag{**MPB**}$$

$$s.t. \quad \text{Eqs. (1c) to (1i) and (2) to (4)}$$

$$\sum_{i \in I} \left(\gamma_i^f - \delta_i^f b_i \sum_{r \in R} (\beta_r m_{ir}) \right) \leq 0 \qquad \forall\ f \in \mathcal{F} \tag{8a}$$

$$\sum_{i \in I} \left(\gamma_i^f - \delta_i^o b_i \sum_{r \in R} (\beta_r m_{ir}) \right) \leq q \qquad \forall\ o \in \mathcal{O} \tag{8b}$$

$$v \geq 0; q \in \mathbb{R}; x \in \mathbb{B}$$

5 Literature review

Allocation of bins and routing problems have been thoroughly studied as separate problems in the MSW related literature [16]. Comprehensive reviews of the study of these problems separately can be found in [20] and [10], respectively. However, the number of works considering integrated approaches is more scarce.

Among the works that consider an integrated approach, [14] presented a study case of the Tunisian city of Sousse, considering uncertainty in waste generation at GAPs. They proposed a transformed formulation to handle stochastic

waste generation and solved the problem in a heuristic fashion: first they applied the k-means clustering algorithm to group the GAPs into sectors and later they applied an exact model solved with CPLEX to determine both the number of bins and the collection route of each sector. They consider that all GAPs are to be collected daily.

Another example is [12], which proposed an integrated approach where the bins allocation problem is solved jointly with the routing schedule. The authors compare different methods to solve this problem based on a Variable Neighbourhood Search (VNS) algorithm, for solving the problem hierarchically – i. e., first solving the bin allocation and then the routing and *vice versa* – and integrated approaches. They found that integrated approaches overcome hierarchical ones.

A further complex approach is presented in [13] for solving an integrated model that aims to simultaneously locate GAPs, size the storage capacity of each GAP (allocate bins) and set the weekly collection schedule and routes in the context of collaborative recycling problem. They solved this problem with an Adaptive Large neighbourhood Search algorithm based on Hemmelmayr's implementation [11]. They performed a sensitivity analysis for several of the parameters, such as available vehicle capacities, visiting schedules or GAPs' storage capacities.

Although integrated models have proven to efficiently handle the trade-off [7, 9], others works have tackled these problems in a sequential fashion. For example, [8] solved the GAP location with while considering that bins of incompatible types – i. e., that cannot be collected by the same vehicle – are not located in the same GAP. Then they applied an heuristic zoning algorithm to define the routes while minimising the number of required vehicles and the total distance. Finally, [21] solved a multi-objective bins allocation problem in which one of the objectives was to minimise the required collection frequency.

Differently from the tactical problem that we address in this paper, other authors have used Bender's decomposition approaches to deal with optimization problems of the strategic level of the MSW logistic chain, mainly considering stochastic parameters (which is a traditional application area of Bender's decomposition). For example, [22] used Bender's decomposition to model a logistic chain of MSW in which organic waste in send from sources into treatment plants to generate power. Uncertainty is considered in waste generation, and power price and demand. Another case are [15], who applied Bender's decomposition to optimize the location and capacity selection of waste transfer stations when considering uncertainty in the operational cost of the stations.

6 Computational experiments

The instances used for these tests are based on simulated scenarios of the city of Bahía Blanca, Argentina. Although this city still has a door-to-door collection system, the local government and citizens are interested in studying more efficient collection systems that allow them to reduce the high logistic costs. In this sense, a community bins-based will simplified the required collection logistic [2, 5]. Particularly the location of 76 GAPs in a central neighbourhood of the

city and the generation rate were obtained from a recent field work in a central neighbourhood of the city [5]. We consider a *homogeneous VRP* by using the standard collection vehicle of Bahía Blanca, a $20\,\mathrm{m}^3$ bin-tipper truck. The GAPs can hold three types of commercial bin with purchasing and maintenance cost (cin_u) 2.76, 3.53 and 5.24 monetary units (m.u.) and capacities (cap_u) 1.1, 1.73 and $3.1\,\mathrm{m}^3$, respectively. Information about the travel time between GAPs was estimated with Open Source Routing Machine[3] using the approach proposed by Vázquez Brust [24]. The algorithms are implemented in Python 3.5, and we use a UB&BC framework called BranDec[4] v0.7. For the benefit of the scientific community, we open-sourced the instances used for the experimentation[5] and implementation. The solver used is CPLEX v12.7 in its default configuration, we disable heuristics when running the UB&BC. We ran the experiments on a computer with Intel Gold 6148 Skylake CPU@2.4GHz and a 4GB RAM limit.

We divide the computational experimentation in two parts. In Section 6.1 we deal with small instances in order to asses the value of the proposed valid inequalities in the resolution approach. Then, in Section 6.2 we explore the performance of the proposed Benders approach in comparison to full MIP when solving more complex instances.

6.1 The value of valid inequalities

In order to explore the impact of valid inequalities in the resolution process we construct instances composed by five GAPs and the Depot. These sample of five GAPs were selected with QGIS Random Selection tool. We consider scenarios with two vehicles and two bin arrangements per GAP, the instances are formatted as "$I/T/n$," where n is the instance number. Figure 1 report the results of solving the resulting problem with:

MIP CPLEX using (**M1**);
MIP + VIs CPLEX using (**M1**) augmented with VIs (2) to (4);
BD our Benders approach; and,
BD + VIs our Benders approach augmented with VIs (2) to (4).

We ran five iterations of each configuration and report the minimum solve time. We can see in Fig. 1 that the VIs are necessary to have reasonable solve times. Both the MIP and our Benders approach benefit from them. When instances grow in size, that is when the time horizon is greater than two days, version with VIs do not manage to solve most instances. This experiment is not enough to tell for certain whether the Benders approach is better than MIP.

6.2 Using more bin arrangements

The complexity of the problem grows with the size of the instance becoming increasingly time consuming for the algorithm. Indeed, we now use a larger set of bin arrangements (set U) for the GAPs in order to have a more complex subproblem with a larger number of binary variables. In Fig. 2 we can see the

[3] http://project-osrm.org/
[4] `https://gitlab.com/Soha/brandec`
[5] http://doi.org/10.13140/RG.2.2.19210.49604

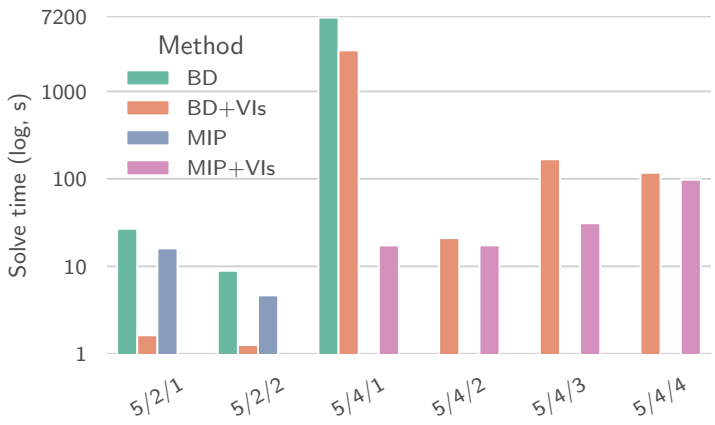


Fig. 1: Results of using different methods, with or without VIs, to solve a set of reduced instances.

time taken to find the optimal solution on a set of instances by our approach (BD) vs. solving the full MIP model with CPLEX (MIP). All the solutions have the valid inequalities (2) to (4) included. Our approach is, on average, more than one order of magnitude faster than using a full MIP. We are able to solve instances up to 7 GAPs, which the MIP cannot.

7 Conclusion

Municipal solid waste management is a critical issue in modern cities. Besides the direct environmental and social problems that can arise when it is mishandled, it usually represents a large portion of the municipal budgetary expense. Therefore, intelligent decision support tools that can efficiently provide this service to the citizens while also reducing the cost of the system can be a major asset for decision makers. This work addresses two common tactical problems that arise in the reverse logistic chain of solid waste: the design of a pre-collection network and the routing schedule of collection vehicles. These problems, which are usually solved individually in the related literature, are interdependent in the sense that the solution to one of the problem affects the other.

This work proposed an integrated approach that solves both problems simultaneously, making the trade-off an intrinsic element of the model. In particular, a new MIP formulation, valid inequalities and resolution approach based on Benders decomposition, using unified branch-and-Benders-cut, were proposed. Since the subproblem contains integer variables, we devised a heuristic for solving the bin allocation problem. Our approach was able to solve real-world instances in the city of Bahía Blanca. Tests performed on small instances showed the competitiveness of the valid inequalities to speed up the resolution process. Then, the resolution of larger instances showed that the proposed Benders approach was more competitive than full MIP. While not yet able to solve full-size instances, our approach holds promises to scale beyond a traditional MIP approach.

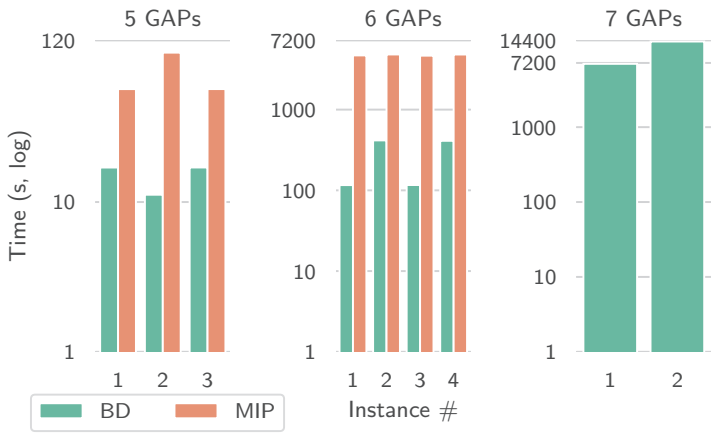


Fig. 2: Comparison of MIP vs. our Benders approach on a variety of scenarios. We report the time in log scale.

Future work includes expanding computational experiments with larger real-world instances to test the scalability of the approach. Another research line is to consider an allocation-first routing-second method. In that case, the master problem would be comparatively simpler than the subproblem. Such an approach would require efficient vehicle routing heuristics to work. We could also explore heterogeneous fleet of vehicles. Indeed, the city of Bahía Blanca already owns a fleet of vans of small capacity for spot operations.

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Proposal of a Heuristic for Cluster Analysis with Application in Allocation of Anaerobic Co-Digesters for Biogas Production

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Abstract. Cluster analysis refers to optimally segmenting a set of entities, and there are several types of algorithms to reach this purpose. It can be applied in decision making, machine learning, data mining, and pattern recognition. This work aims to develop a simple and fast partition heuristic to solve the cluster analysis problem, where the optimality criteria are the smallest distances between the vertices of the same cluster. To verify the proposed heuristic, tests were made in instances ranging from 20 to 5000 nodes and different degrees of complexity. The developed algorithm can be applied to large size datasets were time could be a limitation factor. As an example of application, the heuristic developed was used to choose the location for installing anaerobic co-digesters for the production of biogas in the state of Paraná, Brazil.

Keywords: Cluster Analysis, Heuristics, Biogas.

1 Introduction

Cluster analysis involves optimally partitioning a given set of entities into a predetermined number of mutually exclusive clusters, where the criterion of optimality depends on the application in which the grouping is being employed [1]. Clustering is useful in several exploratory analyses, such as decision making, machine learning, data mining and pattern recognition [2].

Clustering algorithms can be divided into two main approaches: hierarchical and partition. The hierarchical approach produces a series of nested segments, agglomerating or dividing the previous clusters to achieve the desired segmentation. The partition system performs segmentations that optimize a given objective criterion or function. For each approach, there are numerous types of algorithms (genetic algorithm, ant colony, k-means, etc.) that have characteristics that make them more appropriate for solving a particular kind of problem [3].

Within the ways to solve cluster analysis problems is the use of heuristics, which are methods for solving specific problems that use shortcuts to produce solutions that, although not always optimal, are sufficiently adequate in a timely manner. This work aims to develop a simple and fast heuristic to partition a given dataset into a predefined number of clusters in a way that the sum of distances within all clusters is the

smallest possible. We tested the proposed heuristic in instances ranging from 20 to 5000 nodes and different degrees of complexity. This paper's main contribution is present a heuristic that could be applied to large size datasets where time may be a limitation factor and high accuracy isn't crucial. Examples of this work application include multiple facility allocation where an extensive area is considered and the installation of a facility where it can be utilized by a number of persons large as possible (e.g., medical center, supermarket, etc). We applied the heuristic to find the best location for biogas production in the state of Paraná, Brazil. This application was chosen due to the current relevance of renewable energy sources as an alternative to meet the global energy demand without significant environmental impacts [4].

2 Problem definition

The optimization model used was proposed in [3], which was based on the work [1] and is described by (1) to (7).

Parameters:
$k \in K = \{1, ..., M\}$ defines the sets of cluster;
$i, j \in V = \{1, ..., N\}$ defines the sets of points;
M is the total number of clusters;
N is the number of vertices.

Decision variables:
x_{ik} is a binary variable whose value is equal to 1 if the vertex i is in cluster k and 0 otherwise;
y_{ij} is the binary variable whose value is equal to 1 if the vertices i e j are in the same cluster and 0 otherwise;
d_{ij} is the distance between vertices i e j.

Objective Function:

$$Min \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} d_{ij} y_{ij} \tag{1}$$

Subjected to:

$$\sum_{k=1}^{M} x_{ik} = 1, \qquad \forall\, k \in K \tag{2}$$

$$\sum_{i=1}^{N} x_{ik} \geq 1, \qquad \forall\, i \in V \tag{3}$$

$$y_{ij} \geq x_{ik} + x_{jk} - 1, \forall\, i \in V, j \in \{i+1, \dots, N\}, k \in K \tag{4}$$

$$y_{ij} \geq 0, \forall i \in V, j \in \{i+1, \dots, N\} \tag{5}$$

$$x_{ik} \in \{0,1\} \ , \forall \ i \ \in V, k \ \in K \tag{6}$$

$$y_{ij} \in \{0,1\} \ \forall \ i,j \ \in V \tag{7}$$

The objective function (1) aims to minimize the total distance among vertices of the same cluster. The set of constraints (2) assure that each vertex belongs to only one cluster. The set of constraints (3) assure that each cluster has at least one vertex. The constraints (4) and (5) assure that the variable y_{ij} is equal to 1 if both x_{ik} and x_{jk} are equal to 1. The domain of the variables is defined by equations (6) and (7).

3 Proposed heuristics

The methodology developed in this paper was grounded on the work [5] where the authors proposed an algorithm that search for spikes of density, based on the assumption that clusters are density spikes distant from each other and surrounded by a less dense neighborhood. The heuristic proposed in this work and in [5] works only for data defined by a set of coordinates.

First, to identify which regions had the highest density of attributes, the search space is divided into a number of squares, defined as follows: (i) to form the squares, the *X* and *Y* axes are first subdivided into *n*z* segments, were *z* is arbitrarily defined and *n* is the number of clusters desired; (ii) the number of subdivisions of each axis is increased until the sum of attempts that did not improve the objective function is equal to a predetermined value.

Then, to determine the density, sum the quantity of a particular attribute (e.g., points, cities, production potential, number of consumers, etc.) in each region. In sequence, order the regions in relation to density in a decreasing way, after that, select the first *n* regions.

Finally, cluster's centroid is determined by searching, in each of the *n* regions selected previously, the point that has the smallest accumulated distance from the other points belonging to the same square. The heuristic's pseudocode is presented below.

3.1 Pseudocode

While the maximum number of attempts without improvements isn't reached do:

Divide the search space by *n*z*, where $z \geq 0$ and *n* is the number of clusters;
Sum the points or attributes within each region to obtain the density;
Select the *n* densest regions;
For each area selected above, define as cluster's centroid the point with the smallest sum of distances from other points in the same region;
Assign the remaining points to the cluster of the nearest centroid;
Verify if the restrictions were satisfied;
Evaluate the objective function;
If the actual objective function value is better than the previous, then set the best cluster's configuration as the actual solution;

If the value is not better, then add one to the number of attempts without improvement;
Add one to z's value;
Return the best cluster configuration.

4 Results

The method was tested on instances generated by the authors. To obtain the exact solution for the clustering problem on these instances, we developed a program in C++ and solved it using CPLEX 12. The results obtained are in Table 1.

Table 1. Results for the exact solution.

Instance	Nodes	Cluters	Solution	Computing Time (s)	Status	GAP	Lower Bound
A20	20	2	8348.6836	≈505	Optimal		
B20	20	2	8009.9048	≈602	Optimal		
C20	20	2	8201.6025	≈444	Optimal		
D20	20	2	6891.7427	≈218	Optimal		
E20	20	2	8410.6553	≈428	Optimal		
F20	20	2	9365.5303	≈430	Optimal		
G20	20	2	7845.5913	≈487	Optimal		
H20	20	2	6390.4751	≈550	Optimal		
I20	20	2	9667.8535	≈691	Optimal		
J20	20	2	8991.2773	≈446	Optimal		
K20	20	2	12523.0234	≈594	Optimal		
L20	20	2	12014.8584	≈517	Optimal		
M20	20	2	10866.3984	≈454	Optimal		
N20	20	2	10337.6152	≈468	Optimal		
A50	50	4	32359.9023	≈31208	Optimal		
B50	50	4	30562.3027	≈30529	Optimal		
C50	50	4	30824.7422	≈1369	Optimal		
D50	50	4	27175.5898	≈27493	Optimal		
E50	50	4	27483.0547	≈11000	Optimal		
F50	50	4	29114.4160	≈1925	Optimal		
G50	50	4	32634.8594	≈35417	Optimal		
A200	200	4	1216165.875	≈35885	Feasible	0.9978	2694.0615
B200	200	4	1075722.125	≈35958	Feasible	0.9779	23771.430
C200	200	4	1605665.375	≈35737	Feasible	0.9745	41002.098
D200	200	4	1545418.375	≈35933	Feasible	0.9971	4543.4970
E200	200	4	1418379.125	≈35909	Feasible	0.9847	21750.123
F200	200	10	248272.7813	≈35713	Feasible	1	0
G200	200	10	210943.4219	≈35656	Feasible	1	0
H200	200	10	282760.9375	≈35826	Feasible	1	0
I200	200	10	282364.25	≈35613	Feasible	1	0
J200	200	10	311180.5	≈35769	Feasible	0.9999	28.8968
K200	200	10	318806.1875	≈35774	Feasible	1	0
L200	200	10	354271.5	≈35726	Feasible	1	0

M200	200	10	294376.71875	≈35819	Feasible	1	0
N200	200	10	237300.84375	≈35835	Feasible	1	0
O200	200	10	306800	≈35863	Feasible	1	0

The algorithm for the heuristic solution was implemented in Python and executed on an Intel Core i5 1.80GHz RAM notebook. We set the initial value of z as 1 and increased it by one until reach 5 attempts without improvement. The results obtained by the proposed heuristic, along with the comparison with the exact results, are shown in Table 2.

Table 2. Results for the heuristics solution.

Instance	Solution	Difference from the exact solution	Computing Time (s)
A20	8348.6832	≈0	≈2
B20	8009.9048	≈0	≈2
C20	8201.6027	≈0	≈2
D20	6891.7428	≈0	≈2
E20	8410.6554	≈0	≈2
F20	9365.5298	≈0	≈2
G20	7845.5912	≈0	≈2
H20	6390.4749	≈0	≈2
I20	9667.8537	≈0	≈2
J20	8991.2770	≈0	≈2
K20	12523.0237	≈0	≈2
L20	12014.8582	≈0	≈2
M20	11122.5866	+256.188	≈2
N20	10337.6151	≈0	≈2
A50	47627.3856	+15267.5	≈2
C50	30824.7420	≈0	≈2
D50	27303.4368	+127.847	≈2
E50	28732.1027	+1249.05	≈2
F50	29188.0602	+73	≈2
G50	34364.1975	+1729.34	≈2
A200	713661.6293	-502504.2	≈3
B200	597733.9354	-477988.2	≈3
C200	969365.1094	-636300.3	≈3
D200	848980.4534	-696437.9	≈3
E200	829846.7959	-588532.3	≈3
F200	202176.5698	-46096.21	≈4
G200	179009.6952	-31933.73	≈4
H200	203059.6423	-79701,3	≈4
I200	166949.95	-115414.3	≈4
J200	195687.4640	-115493	≈4
K200	170802.1563	-31709817	≈4
L200	297823.4845	-35129327	≈4
M200	240254.331	-29197418	≈4
N200	185526.2464	-23544558	≈4
O200	194504.4108	-30485496	≈4

Table 1 show that the heuristic obtained values near the optimal solution obtained by the exact method in a much smaller time. It is also possible to verify that in the cases where the exact method couldn't reach the optimal solution, the value achieved by the heuristic was better. The heuristic proposed was also tested in larger instances, obtained in [6]. The values of the objective functions and the test execution time for these instances are shown in Table 3, and the distribution of clusters for instances "S1" and "S2" is illustrated in Figure 1.

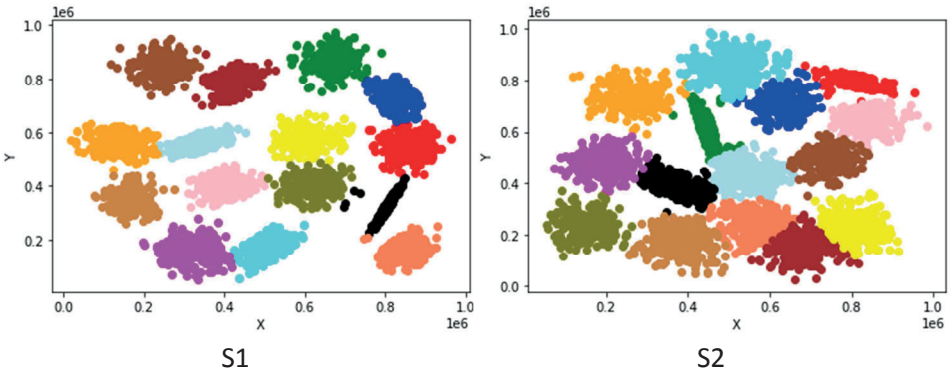

Fig. 1. Results for "S1" and "S2" instances.

For "S" instances the algorithm´s performance varied significantly as the size of the data set increased and several points were assigned to the wrong clusters, as can be seen in Figure 1, which shows the distribution of the points. This problem could be solved by considering the distance between the density spikes, selecting as clusters the densest locations that are the most far from the others. However, the attempts made with this methodology had the execution time as a limiting factor, both because Python is an interpreted language that needs special compilation libraries to run faster, and the configuration of the computer used to run the tests.

Table 3. Results for the "S" instances.

Instance	Nodes	Clusters	Exact solution[1]	Proposed heuristic results	Computing Time
S1	5000	15	41304133758.6787	42278068222.2418	≈8min
S2	5000	15	50100392668.3150	51514320860.6473	≈8min
S3	5000	15	56666466350.1669	61896790663.16	≈8min
S4	5000	15	53703664418.8502	64399923015.9137	≈8min

[1]Value of the objective function calculated using the ground truth centroids found in [6]

5 Application and final considerations

The developed heuristic was applied to choosing locations for installing anaerobic co-digesters for the production of biogas in the state of Paraná, Brazil. The solution aimed to minimize the transport distances, the total cost of the supply chain, and the associated carbon emissions. The main logistical activities in the biogas supply chain are substrate harvesting or collection, substrate storage, substrate transport, biogas production, biogas transport, and consumption of biogas [7].

Geography and distance can be essential factors because the transformation of biomass into energy is highly dependent on geographical factors since the supply of substrates and the points of demand for biogas are often widely dispersed. The use of cluster analysis to solve this problem is supported by the fact that deploying regional or centralized anaerobic digesters is an effective way to serve various rural establishments and consumers [8].

Biogas is formed in nature by the biological degradation of organic matter under anaerobic conditions. The main components of biogas are methane and carbon dioxide, which can be captured to generate energy in heat and electricity. The generation of biogas can be maximized by using techniques such as co-digestion, which is the simultaneous digestion of two or more organic substrates. Co-digestion can increase biogas production by 25% to 400%, compared to isolated digestion of the same substrates [9]. In addition to increased biogas production, co-digestion also provides the following benefits: (i) improves the process stability; (ii) decreases the concentration of inhibitory substances; (iii) better balance of nutrients and moisture; (iv) increase the organic load; and (v) economic advantages due to equipment and cost-sharing [10].

In this case study, the choice of raw materials that will compose the mixture fed in the co-digester was made based on the article [11], where the tailings produced in Brazil were quantitatively and qualitatively analyzed to list which ones had the greatest potential for biogas generation. According to [11], more than 60% of the total biogas generation potential in Brazil comes from cattle manure, followed by sugarcane vinasse, swine manure, and poultry manure.

We obtained data on the number of heads of each of the types of farming considered and of tons of sugarcane produced in each of the 399 Paraná's cities from [12]. From these data, we calculated the biogas production potential for each city in the state. To calculate the potential for biogas production from the manure of different animals we used equation (8) obtained from [11].

$$Q_{CCH4} = Q_{SCH4} = Q_{PCH4} = \frac{I_M . NA . f_m . \varepsilon}{1000} \quad (8)$$

Where:

Q_{CCH4} is the potential for biogas production from cattle manure (m³/year);
Q_{SCH4} is the potential for biogas production from swine manure (m³/year);
Q_{PCH4} is the potential for biogas production from poultry manure (m³/year).

I_M is the manure generation rate of the animal herd (kg/year), the adopted values were: 10 for cattle manure, 2,25 for swine manure and 0,18 for poultry manure. These values were found in [13] *apud* [14] and [15];

NA number of animal herds in all territory;

f_m factor of biogas production by manure type (m^3CH_4/t), the adopted values were: 12 for cattle manure, 12 for swine manure and 27 for poultry manure. These values were found in [13] *apud* [14] and [15];

ε collection efficiency in bio-digester (adopted to be 90% as in [11]).

To calculate the potential for biogas production from sugarcane vinasse we used equation (9), obtained from [11].

$$Q_{VCH4} = P_V . T_S . COD_V . E_{fv} . f_V . E_{cV} \quad (9)$$

Where:

Q_{VCH4} is the potential for biogas production from sugarcane vinasse (m^3/year);;

P_V is the vinasse production by mass unity of sugarcane (m^3/year);

T_S is the sugarcane produced amount (tons) ;

COD_V is the typical COD for vinasse, whose value was assumed as equal to 35,5 kg/m^3 [16];

E_{fv} is the removing efficiency of vinasse organic load in an anaerobic reactor, whose value was assumed as equal to 62% based on [17];

f_V is the specific factor of biogas production per mass of COD removed in the anaerobic reactor, whose value was assumed as equal to 0,29 $m^3/kgCOD_{removed}$ and obtained from [18];

E_{cV} is the collecting efficiency of biogas in the anaerobic reactor, assumed as 90%.

The total methane production potential of each city was calculated using equation (10). The map of production potential's obtained is shown in Figure 2.

$$Pot_{ch4} = Q_{VCH4} + Q_{CCH4} + Q_{SCH4} + Q_{PCH4} \quad (10)$$

Where:

Pot_{ch4} is the total biogas production potential (m^3/year);

The heuristic developed was used to segment the state of Paraná into seven clusters to minimize transport distances and the total cost of the biogas generation supply chain. The number of cluster was defined arbitrarily.

First, to identify which regions had the highest potential density for biogas production, the geographical space of Paraná was subdivided into a number of segments, the initial value of z was set as 0.5. The number of subdivisions of each axis was increased by one until reach five attempts that failed to improve the objective function. Then, to determine the density of the regions previously obtained, each city's total biogas production potential in the region was added. The regions were then ranked

according to the density of the biogas production potential in a decreasing way. After that, the first *n* regions were selected.

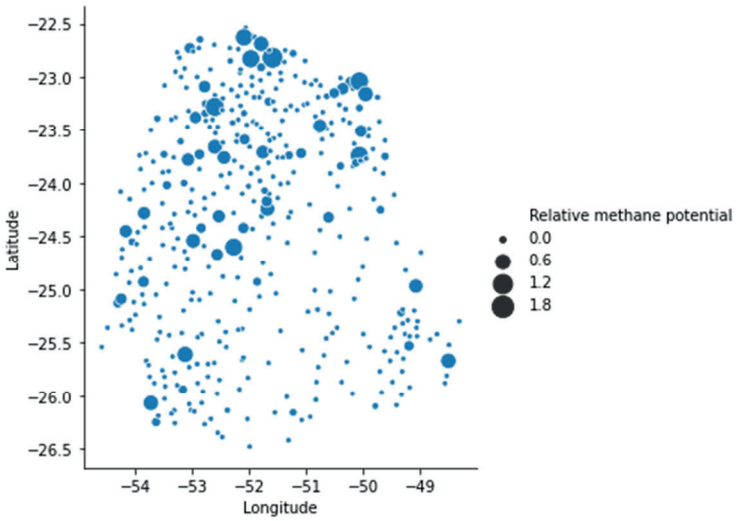

Fig. 2. Relative methane production potential for each city in the state of Paraná, Brazil.

To choose the centroid we considered not only the distance from other points but also the production differences, to do so, we multiplied the distance by the methane potential, making the centroids closer to high production points. Finally, each city was assigned to the clusters of the nearest centroid. The results obtained are shown in Figure 3.

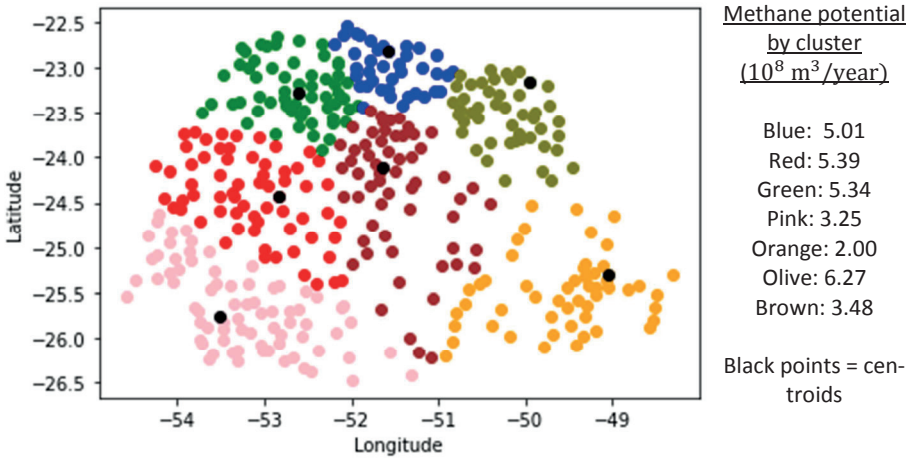

Fig. 1. Application of the cluster analysis heuristic for an anaerobic co-digester allocation in the state of Paraná, Brazil.

Comparing Figures 2 and 3, it is possible to observe that the algorithm was able to identify as centroid the spots with higher potential for methane production. We can conclude that despite the simplicity of the proposed heuristic, it can obtain satisfactory results for different sizes of spaces and numbers of clusters. Also, the technique is flexible and can be easily adapted to solve problems with different scopes.

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Optimal reverse supply chain design: the case of empty agrochemical containers.

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Abstract. The growing use of agrochemicals added to the harm that contaminated containers cause to the environment and to the health of the population, make it necessary to establish a reverse supply chain for the recovery and correct treatment of empty containers. Current regulations establish that they must be triple-rinsed and sent to collection centers, where containers are consolidated and shipped to treatment/recycling plants. Containers can also be sent to these plants directly. Given this problem, this contribution proposes an MILP multiperiod model to define the optimal configuration and operation of the reverse supply chain network of empty agrochemical containers along a given planning horizon. Provided a superstructure including farms and the location of the potential nodes (collection centers and plastic treatment plants), the model determines which facilities to install and when, their corresponding sizes, as well as how they would operate along the planning horizon. In addition, the model establishes the material flows among the various nodes in each planning period (network topology). The proposed model has been verified by addressing a realistic case study, which has been solved under different scenarios, exhibiting good computational performance. The obtained results allow reaching satisfactory conclusions in relation to model scalability and sensitivity.

Keywords: Reverse Logistics · Supply chain design and planning · Empty agrochemical containers ·Mixed-integer linear programming model

1 Introduction

Current supply chains are not limited to unidirectional product flows from manufactures to consumers. On the contrary, they need to deal with opposite material flows devoted to the reuse, recycling and/or final disposal of products, parts, as well as packaging and empty product containers. Managing these inverse flows confronts companies with novel challenges that need to be analyzed under the umbrella of reverse logistics. It can be defined as the process of planning, implementing and controlling backward flows of raw materials, in process inventory, packaging and fi-

nished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal [1].

This contribution addresses the design of a reverse supply chain of agrochemical containers. It is intended to collect and thoroughly clean the plastic vessels, once they have been emptied and triple-rinsed, with the aim of recycling/using the plastic, decontaminating the washing water, while minimizing the associated environmental and health risks. The problem of configuring such network along a given planning horizon implies establishing: (i) the number and location of collection centers – intermediate points for collecting containers – , as well as plastic treatment plants to be installed, (ii) the time period in which each facility will be installed and the ones in which it will operate, (iii) the capacities of the various storage and processing facilities, (iv) for each time period, which are the flows of materials between farms, which generate the containers, and the collection/treatment points, as well as the flows between collection centers and plastic treatment plants. This problem is addressed by means of a multi-period MILP (Mixed Integer Linear Programming) model that is able to tackle the challenges previously presented while minimizing the total actual discounted cost of the network.

This contribution is organized as follows. Section 2 contains a brief literature review on the design of reverse supply chains. The mathematical model is presented in Section 3. In Section 4, a realistic case-study, which allows testing the formulation, is described. Computational results and a sensitivity analysis are presented in Section 5. The contribution ends with concluding remarks and a summary of future work.

2 Literature review

Facility location decisions play a critical role in the design of supply chain networks, as pointed out in [2]. This review article presents a comprehensive analysis of several facility location approaches by identifying basic characteristics (number of products, number of periods of the planning horizon, type of network structure, uncertainty consideration, etc.) that models must capture in order to address different kinds of supply chain planning problems that are of practical interest. It considers both the typical node location-allocation decisions and their integration with other decisions that are relevant to problems of optimal design and planning of supply chain networks. This review paper shows that the supply chain configuration and planning problems have increasingly drawn the attention of the scientific community during the last two decades. In addition, sustainability aspects started playing a central role, thus impacting not only on the objectives to be pursued – economic, environmental and social – [3], but also on the reverse flows of materials to be considered [4].

Reverse logistics is defined as the process of planning, implementing and controlling backward flows of materials (raw materials, in-process inventory, packaging and finished goods), from a manufacturing, distribution or use point, to a point of recovery and/or proper disposal. Two main types of reverse logistics design and planning problems can be identified [2]: (i) The ones associated with closed-loop networks, where the reverse network is fully integrated with the forward chain, thus allowing

the simultaneous definition of the optimal distribution and recovery networks, and; (ii) Recovery network problems, i.e. the ones that are limited to recovery and/or disposal activities. Regarding these last ones, [5] proposes a mathematical programming framework that accommodates several characteristics of practical relevance: a multi-period setting, modular capacities, capacity expansion of the facilities, reverse bills of materials, variable operational costs, among other features. Other generic mathematical programming formulations to address reverse network configuration problems were proposed in [3-4]. In particular, [3] presents a multi-objective model that integrates the three dimensions of sustainability: economic, environmental, and social.

Despite the fact that the number of scientific publications related to the reverse logistics domain has been steadily growing, showing the increasing importance of the field due to the environmental awareness of the society, generic models cannot address all the situations that are found in practice yet. Even for the subfield of solid waste management, [6] have pointed out the various specific features that are to be considered, which may need to be further adapted under an extended producer responsibility approach.

Regarding the reverse supply chains of empty agrochemical containers, few contributions have been found. Lagarda-Leyva [7] addressed the reverse supply chain of agrochemical plastic containers associated with Roma tomato production in a Mexican region. The contribution proposed causal conceptual models that allow developing Forrester's dynamic models that, in turn, have been employed to simulate and assess the operation of the system under dynamic conditions within three different scenarios. Recently, [8] reported a preliminary approach to address the design of the reverse network of empty agrochemical containers in a region of Buenos Aires, Argentina. The proposal includes two MILP formulations. The first one is a single period facility location model that allows selecting, out of a set of potential places, the settings of temporary collection centers (CATs) and a main gathering operation site (OP), where the containers are get together. The potential facilities have fixed capacities. In addition, their operation and installation costs are omitted. The modeling of material flows and transportation costs is also very simple since the transportation from farms to collection centers is not taken into account (farms are not part of the problem). The second model, which must be applied to the solution of the first one, addresses the routing problem associated with the movement of empty containers from CATs to the main gathering point.

It can be concluded that the optimal configuration of the reverse supply chain network of empty agrochemical containers is still a challenging problem that deserves attention and will be addressed in the remaining sections of this contribution.

3 Mathematical programming formulation

In this Section a multi-period mixed-integer linear programming (MILP) model for the design of the reverse logistics network previously described is presented.
Given:

- a planning horizon of a certain length,

- the set of farms, each one generating a pre-specified number of empty containers in each period of the planning horizon,
- the superstructure that includes all the potential/existing collection centers and possible/existing plastic treatment plants, as well as the farms – i.e. all the nodes to be considered for the network design – and their interconnections – i.e. the arcs and their associated distance,
- the set of possible discrete sizes of collection centers/treatment plants,
- the sizes of the facilities already installed at the beginning of the planning horizon,
- maximum and minimum storage capacities for a collection center/treatment plant of a given size,
- maximum and minimum processing capacities of each treatment plant size,
- maximum capacity of each type of truck to be used,
- number of periods required by a new facility to start operating,
- installation and fixed operational cost of collection centers/treatment plants,
- variable processing cost of treatment plants,
- transportation cost per unit distance between the different types of nodes.

Determine:

- which collection centers and plastic treatment plants to install, and when to install them,
- capacity of each facility to be built,
- which collection centers and plastic treatment plants to operate along each period of the planning horizon
- container flows between farms and collection centers, farms and treatment plants and collection centers and treatment plants during each planning period.

So as to minimize the total actual discounted cost of the network.

3.1 Model assumptions

It is assumed that: (i) all the model parameters are deterministic, i.e. no uncertainty is considered, (ii) the containers that are generated in a given period must be collected and treated in the same period, (iii) collection centers and plastic treatment plants to be installed are of discrete capacities, (iv) variable operating costs are taken into account only for plastic treatment plants, (v) transportation costs only consider the distance traveled and omit the load of the vehicles.

3.2 Nomenclature

Sets/indices

F/f	farms
J/j	collection centers
P/p	plastic treatment plants

J^i / P^i	subset of transitory centers/treatment plants that are already installed at the beginning of the planning horizon
M/m	set of available sizes of collection centers
N/n	set of available sizes of plastic treatment plants
$T/t, t'$	time periods

Parameters

g_{ft}	number of containers to be generated by farm *f* during period *t*
$d_{fj}/d_{fp}/d_{jp}$	distance between nodes of different types
k_m^{min}/k_n^{min}	minimum capacity of a collection center/treatment plant of size *m/n*
k_m^{max}/k_n^{max}	maximum capacity of a collection center/treatment plant of size *m/n*
nt^j / nt^p	number of time periods required by a new collection center/treatment plant to start operating from the period it is installed
$c^{fj}/c^{fp}/c^{jp}$	transportation cost per distance unit between the different nodes of the network
ir	interest rate
fc_m/fc_n	fixed cost of operation of a collection center/treatment plant of size *m/n*
vc	variable production cost of plastic treatment plants
cc_m^j/cc_n^p	construction cost of a collection center/treatment plant of size *m/n*
ec_n	equipment cost of a treatment plant of size *n*
cap	loading capacity of the trucks that travel between collection centers and treatment plants
nf_{ft}	number of trips required to transport the total generation of containers of farm *f* during period *t*
$nmax$	$max\ (nt^j, nt^p)$. number of periods that must be considered previous of the start of the planning horizon for the installation of facilities

Decision variables

Binary variables

X_{jm}/X_{pn}	equal to one if collection center *j*/treatment plant *p* of size *m/n* is installed
Y_{jt} / Y_{pt}	equal to one if collection center j/treatment plant *p* operates in period *t*
I_{jt}/I_{pt}	equal to one if collection center j/treatment plant *p* is installed in period *t*

Positive variables

$S_{fjt}/S_{fpt}/S_{jpt}$	number of containers sent between nodes of different types in period *t*

3.3 MILP formulation

Using the above definitions, the model is formulated as follows.

$$\text{Min} \quad \sum_{t} \frac{Icc_t + Icp_t + Vcp_t + Ocj_t + Ocp_t + Tc_t^{fj} + Tc_t^{fp} + Tc_t^{jp}}{(1+ir)^{t-1}} \tag{1}$$

$$s.t. \quad g_{ft} = \sum_{\forall j \in J} S_{fjt} + \sum_{\forall p \in P} S_{fpt} \qquad \forall f \in F,\ \forall t \in T > nmax \tag{2}$$

$$\sum_{\forall f \in F} S_{fjt} = \sum_{\forall p \in P} S_{jpt} \qquad \forall j \in J, \forall t \in T > nmax \tag{3}$$

$$\sum_{\forall t,\ t' + nt^j \le t} I_{jt'} \ge Y_{jt} \qquad \forall j \in J,\ j \notin J^i, \forall t \in T \tag{4}$$

$$\sum_{\forall t,\ t' + nt^p \le t} I_{pt'} \ge Y_{pt} \qquad \forall p \in P,\ p \notin P^i, \forall t \in T \tag{5}$$

$$\sum_{\forall m \in M} X_{jm} = \sum_{\forall t \in T} I_{jt} \qquad \forall j \in J,\ j \notin J^i \tag{6}$$

$$\sum_{\forall n \in N} X_{pn} = \sum_{\forall t \in T} I_{pt} \qquad \forall p \in P,\ p \notin P^i \tag{7}$$

$$\sum_{\forall m \in M} X_{jm} \le 1 \qquad \forall j \in J \tag{8}$$

$$\sum_{\forall n \in N} X_{pn} \le 1 \qquad \forall p \in P \tag{9}$$

$$\sum_{\forall f \in F} S_{fjt} \le k_{m=max}^{max}\ Y_{jt} \qquad \forall j \in J, \forall t \in T,\ t > nmax \tag{10}$$

$$\sum_{\forall f \in F} S_{fjt} \le \sum_{\forall m \in M} k_m^{max}\ X_{jm} \qquad \forall j \in J, \forall t \in T,\ t > nmax \tag{11}$$

$$\sum_{\forall f \in F} S_{fpt} + \sum_{\forall j \in J} S_{jpt} \le k_{n=max}^{max}\ Y_{pt} \qquad \forall p \in P, \forall t \in T,\ t > nmax \tag{12}$$

$$\sum_{\forall f \in F} S_{fpt} + \sum_{\forall j \in J} S_{jpt} \le \sum_{\forall n \in N} k_n^{max}\ X_{pn} \qquad \forall p \in P, \forall t \in T,\ t > nmax \tag{13}$$

$$\sum_{\forall f \in F} S_{fjt} \ge k_{m=1}^{min}\ Y_{jt} + \sum_{\forall m \in M,\ m>1} (k_m^{min} - k_{m=1}^{min})(Y_{jt} + X_{jm} - 1) \qquad \forall j \in J, \forall t \in T,\ t > nmax \tag{14}$$

$$\sum_{\forall f \in F} S_{fpt} + \sum_{\forall j \in J} S_{jpt} \ge k_{n=1}^{min}\ Y_{pt} + \sum_{\forall n \in N,\ n>1} (k_n^{min} - k_{n=1}^{min})(Y_{pt} + X_{pn} - 1) \qquad \forall p \in P, \forall t \in T,\ t > nmax \tag{15}$$

$$Icc_t = \sum_{\forall j \in J,\ j \notin J^i} \sum_{\forall m \in M} cc_m^j \left(I_{jt} + X_{jm} - 1\right) \qquad \forall t \in T \tag{16}$$

$$Icp_t = \sum_{\forall p \in P,\ p \notin P^i} \sum_{\forall n \in N} (cc_n^p + ec_n) \left(I_{pt} + X_{pn} - 1\right) \qquad \forall t \in T \tag{17}$$

$$Vcp_t = \sum_{\forall p \in P} vc \left(\sum_{\forall f \in F} S_{fpt} + \sum_{\forall j \in J} S_{jpt} \right) \qquad \forall t \in T \tag{18}$$

$$Ocj_t = \sum_{\forall j \in J} \sum_{\forall m \in M} fc_m \, (Y_{jt} + X_{jm} - 1) \qquad \forall t \in T \qquad (19)$$

$$Ocp_t = \sum_{\forall p \in P} \sum_{\forall n \in N} fc_n \, (Y_{pt} + X_{pn} - 1) \qquad \forall t \in T \qquad (20)$$

$$Tc^{fj}{}_t = \sum_{\forall f \in F} \sum_{\forall j \in J} c^{fj} \; 2 \; d_{fj} \; \frac{S_{fjt}}{g_{ft}} \; nf_{ft} \qquad \forall t \in T \qquad (21)$$

$$Tc^{fp}{}_t = \sum_{\forall f \in F} \sum_{\forall p \in P} c^{fp} \; 2 \; d_{fp} \; \frac{S_{fpt}}{g_{ft}} \; nf_{ft} \qquad \forall t \in T \qquad (22)$$

$$Tc^{jp}{}_t = \sum_{\forall j \in J} \sum_{\forall p \in P} c^{jp} \; 2 \; d_{jp} \; 1.2 \; \frac{S_{fpt}}{cap} \qquad \forall t \in T \qquad (23)$$

The objective function, given by expression (1), comprises the different costs involved in the design and operation of the logistics network throughout the planning horizon: (i) installation costs of collection centers and treatment plants, (ii) variable costs of handling empty containers in treatment plants, (iii) fixed operation costs of facilities, and (iv) transportation costs between the different nodes of the network. In order to determine how much future projected cash flows are worth at present, these cost components are affected by an annual interest rate, according to the multi-period total discounted cost formula given by (1). The model includes constraints (2)-(23).

Eq. (2) prescribes that all the containers generated by a farm in a certain period, must be sent to a collection center and/or to a treatment plant in the same planning period. Similarly, Eq. (3) states that all the containers that are received by a collection center in a given period must be sent to a plastic treatment plant in the same period.

Expression (4) assures that a collection center can operate in a certain period only if it has been installed in a previous one. Expression (5) forces treatment plants to obey the same restriction. Eq. (6) states that if a collection center is installed in one of the periods, it must adopt one of the *m* available sizes. In a similar way, Eq. (7) prescribes that if a plastic treatment plant is installed in one of the periods, it must be of one of the *n* available sizes. Expressions (8) and (9) force that every collection center/treatment plant that is installed should adopt just one of the available sizes.

According to inequalities (10) and (11), the number of containers sent to a given collection center in each period, should not overpass the maximum storage capacity corresponding to the installed size. The maximum capacity of each treatment plant to be built is captured by means of expressions (12) and (13). They have the same rationale as (10) and (11). Following analogous ideas, the minimum capacity of each collection center and plastic treatment plant to be installed is given by expressions (14) and (15), respectively.

Expressions (16) - (23) capture the different cost terms participating in the objective function. Eq. (16) defines the investment cost of new collection centers in each period, Icc_t. Similarly, Eq. (17) captures the investment cost of new treatment plants in each period. It takes into account both the construction cost and the equipment cost associated with the size of the plant to be installed. It should be noted that these costs are calculated by applying scale economies. Variable costs per period are only consi-

dered for plastic treatment plants, as shown in Eq. (18). They take into account unit processing cost and the total number of containers sent to each plant in each period. The fixed operation cost associated with collection centers in each period, Ocj_t, is given by Eq. (19). The fc_m cost parameter depends on the adopted size m. Similarly, Eq. (20) establishes the fixed operation cost of treatment plants in each period, Ocp_t. The fc_n cost depends on the size n that is adopted for each treatment plant. The transportation costs from farms to collection centers for each one of the planning periods is captured by Eq. (21). As seen, round trips are taken into account by multiplying the transportation cost per distance unit from farm f to collection center j, c^{fj}, by twice the distance between these nodes. In turn, this is multiplied by the proportion of the number of trips required to transport the total generation of containers of the farm that are just sent to the collection center. It should be noted that nf_{ft} is calculated considering 1.5 times the actual number of trips that would be required if the complete vehicle capacity would have been employed. This assumption relies on the fact that most of the trips are made with less than the maximum allowed load. The proportion is calculated by dividing the number of containers sent from each farm to each collection center in a given period, by the container generation of the farm in such a period. The transportation cost from farms to treatment plants, for each planning period, is captured by Eq. (22) in the same way the transportation cost between farms and collection centers has been estimated. Finally, the transportation cost from collection centers to treatment plants, for each planning period, is calculated by Eq. (23). In this case, it is considered 1.2 times the total number of required trips, since a better container load consolidation can be carried out.

4 Case study description

The MILP model presented in the previous section has been implemented to establish the reverse logistic network configurations and operation policies associated with several scenarios of a realistic case study. Such case study corresponds to the handling and treatment of empty agrochemical containers in three northern departments of the Santa Fe province, Argentina. This province has one of the most significant agricultural productions in the country. Consequently, it has one of the largest generations of empty agrochemical containers, which are used to control unwanted pests and weeds of crops. As already presented, this reverse supply chain comprises three types of nodes: farms, transitory collection centers, and treatment plants. In these last facilities the plastic is thoroughly cleaned and subsequently pelletized. In addition, the water that is employed in the process is decontaminated before it is recycled, so as to minimize the use of fresh water. Treatment plants can also act as collection centers.

The operation of this recovery system is regulated by national law 27279, which is implemented in a very incipient way in Argentina. This law prescribes that empty agrochemicals containers must be triple-rinsed in farms, which are also responsible for their shipment to collection centers and/or treatment plants. Unfortunately, the system does not work well in practice, farmers fail to meet their obligations and there are not enough collection centers installed - which causes both high transportation

costs and a large carbon footprint. Furthermore, government agencies do not have tools to assess how the law can be satisfactorily complied with, from an economic and environmental perspective, by establishing a proper recovery network. All these elements allow concluding that the problem deserves the attention of the scientific community.

Since this case study considers strategic and tactical decisions, it will be simplified in order to reduce the dimensionality of the resulting mathematical models. Therefore, aggregated farms of approximately 500 hectares will be defined by grouping neighboring farms and assigning to them a fictitious location and an aggregate number of containers. Though it is a simplification, this assumption is pretty common in supply chain strategic decision making problems, which generally consider aggregated products, aggregated customers, or as in this case aggregated farms. The explicit consideration of farms is one of the main differences between the proposed approach and the first model reported in [8].

The number of containers generated per year by each farm has been obtained as a random parameter whose value lies between the minimum and maximum amounts of agrochemicals that are annually applied per hectare, multiplied by the number of hectares where agrochemicals are employed. These random values were also affected by a slight increasing tendency in order to represent that in this region open field livestock activities are being replaced by agricultural ones. The location of potential collection centers that has been considered coincides with the one of municipalities and counties located in the region of interest. With regard to the transportation of empty containers, according to current regulations in Argentina, the vehicles employed to make movements from farms to collection centers and/or treatment plants, should be pick-up vans, having a capacity limit that has been considered in the model. On the other hand, the transportation from collection centers to treatment plants is done by means of trailer trucks having a much greater capacity and lower transportation costs.

Initially, a simple base case has been tackled. It takes into account a superstructure composed of 300 farms, 20 potential collection centers, 8 potential treatment plants and no existing facilities that are already installed. Two different capacity modules for collection centers and treatment plants – i.e. two discrete sizes for each type of facility – have been allowed for. The planning horizon considers 6 years of operation of the collection-treatment system, plus an initial year for the installation of the first facilities. Thus, during the initial year the system does not operate, but the required facilities are being built. This base case has been further extended to test the scalability of the model and its sensitivity to changes in the number of farms, the number of potential collection centers/treatment plants, as well as the length of the planning horizon.

5 Computational results

The model has been implemented in GAMS 23.6, running on an Intel Core i8 computer, with 3.4 GHz, 8 GB of RAM, and using CPLEX as a solver. Initially, the model – expressions (1) to (23) – was solved to assess its computational performance.

The optimal solution corresponding to the base case was reached in 3283s of CPU. Since this is the simplest case of those evaluated, and the CPU time was considerably high, a two-step relaxation approach was proposed to increase the computational efficiency. The proposed approach works as follows. In the first stage, the model composed of expressions (1) to (23) is solved as a linear formulation, relaxing all the binary variables. In a second stage, the original model is solved, but variables I_{jt} and I_{pt} are fixed to zero in those cases having such value in the relaxed model solution. The remaining binary variables – those having a value greater than zero in the relaxed model solution – are given freedom to take either one or zero values. This relaxation approach proved to be quite effective in all the examples that have been solved.

Fig. 1 depicts the optimal solution of the base case, which was obtained in 1565 s. Thus, the same solution was reached with a reduction of 52.33% in the CPU time. During the initial year seven collection centers (red dots) and two treatment plants (black squares) are installed, and they operate along the whole planning horizon. Two collection centers are of the smallest size, with a maximum capacity of 5,000 containers per period. The remaining five correspond to the larger size, being able to handle up to 10,000 containers per period. One small and one large treatment plant are installed, with a maximum capacity of 60,000 and 100,000 empty containers, respectively.



Fig. 1. Optimal solution for the base case problem. Seven collection centers (red dots) and two treatment plants (black squares) are installed previous to the beginning of the planning horizon.

In order to analyze the model scalability and to test its response to changing conditions – i.e. to make a simple sensitivity analysis –, several additional scenarios have been solved using different data sets. Tables 1 and 2 summarize some of the scenarios that have been addressed. All the examples were solved to optimality if the optimal solution was found within 10000 s. Otherwise, a 5% gap was fixed as the stopping criterion, with the exception of one case in which a 10% gap was adopted. The sizes of the resulting models, as well as the computational results, are presented in Table 3. This table reports the statistics corresponding to the relaxation methodology. However, it should be remarked that in all the cases, the same solutions have been obtained when the speed-up approach is omitted, i.e. when solving the regular model. The following paragraphs present an analysis of the 10 examples that have been tackled.

Scenario 1 duplicates the number of farms with respect to the base case, but keeps constant the number of potential collection centers and plastic treatment plants. As

shown in Table 3, the number of binary decision variables does not increase, but the continuous ones almost duplicate, as well as the number of constraints. No optimal solution was obtained within 10000 s, but a solution with a 5% of relative gap was reached in 3099 s. The attained solution comprises the same number of collection centers as the base case solution, but has two more treatment plants. All the installed collection centers are of the large size. Regarding treatment plants, two small and two large are selected. In this way the capacity of the network is increased in order to serve a greater number of farms. All facilities are installed during the first period and operate along the whole planning horizon.

Table 1. Summary of some of the different dimension analyzed scenarios.

	Farms	Possible Collection Centers	Possible Treatment Plants	Horizon length
Base Case	300	20	8	6
Scen. 1	600	20	8	6
Scen. 2	300	20	8	12
Scen. 3	300	20	16	6
Scen. 4	300	40	8	6

Table 2. Summary of some of the different analyzed scenarios disturbing parameters.

	Disturbed parameter	Direction and intensity of disturbance
Scen. 5	Containers generation	50% reduction in period 3
Scen, 6	Containers generation	Generalized gradual decrease
Scen. 7	Transportation costs	10% increase
Scen. 8	Transportation costs	20% increase
Scen. 9	Installation costs	10% increase
Scen. 10	Installation costs	20% increase

Table 3. Computational results corresponding to the different scenarios.

	Total Variables	Binary variables	Total constraints	Objective Function	CPU s	Relative Gap
Base Case	52,335	392	2,855	1,582,355.44	1,565	0,00
Scen. 1	119,848	392	5,184	2,850,718.12	3,099	0,05
Scen. 2	113,326	728	6,558	1,940,178.00	215*	0,00
Scen. 2	113,326	728	6,558	1,940,178.00	9,758#	0,10
Scen. 3	79,320	504	3,832	1,582,355.44	4,403	0,00
Scen. 4	104,908	672	4,484	1,511,971.51	9,715	0,05
Scen. 5	52,335	784	2,855	1,559,379.32	3,489	0,00
Scen. 6	52,335	784	2,855	1,462,987.45	1,634	0,00
Scen. 7	52,335	784	2,855	1,542,416.85	1,258	0,00
Scen. 8	52,335	784	2,855	1,571,170.39	1,558	0,00
Scen. 9	52,335	784	2,855	1,618,496.74	1,308	0,00
Scen. 10	52,335	784	2,855	1,723,330.16	2,489	0,00

*Base Case solution taken for the five initial periods

No solution given to the solver, 10 periods considered all at once.

Scenario 2 takes into account the same superstructure as the base case, but doubles the length of the planning horizon. This leads to duplication in the number of continuous and binary variables, as well as the number of constraints. This more challenging scenario has been tackled with two different solution approaches. The first one considers the base case solution as given, and extends the horizon to evaluate potential new facilities. In this case, the optimal solution has been found in only 215 s. The second approach does not resort to any initial network and the 10 periods are taken into account from the beginning. A solution with a gap of 10% has been reached in 9758 s. The same solution (see Fig. 2) is obtained in both cases. It comprises twelve facilities: 9 collection centers and 3 treatment plants, all of which are installed during the initial period, with the exception of one treatment plant, which is built in period 5. The sizes of the various facilities are summarized in Table 4.

A comparison of the solutions corresponding to the base case and scenario 2 shows that the effect of having a longer planning horizon is to increase the investment in the installation of facilities with the aim of reducing transportation costs, that otherwise would have been much higher. In fact, the base case solution has as its main cost components the installation and transportation ones, with a participation of 56.6 % and 18.17%, respectively. In the case of scenario 2 solution, the participation of these components changes to 52.99% and 20.98%, respectively, despite the fact that three more facilities are installed.



Fig. 2. Optimal solution corresponding to scenario 2. Nine collection center (red dots) and three treatment plants (black squares) are installed previous to the beginning of the planning horizon.

Table 4. Facilities to be installed in each one of the different scenarios.

	Collection centers	Treatment plants	Size of collection centers	Size of treatment plants
Base Case	7	2	2 small, 5 large	1 small, 1 large
Scen. 1	7	4	all large	2 small, 2 large
Scen. 2	9	3	5 small, 4 large	2 small, 1 large
Scen. 3	7	2	2 small, 5 large	1 small, 1 large
Scen. 4	12	2	9 small, 3 large	1 small, 1 large
Scen. 5	7	2	2 small, 5 large	1 small, 1 large
Scen. 6	6	2	1 small, 5 large	1 small, 1 large
Scen. 7	7	2	2 small, 5 large	1 small, 1 large
Scen. 8	7	2	2 small, 5 large	1 small, 1 large
Scen. 9	7	2	2 small, 5 large	1 small, 1 large
Scen. 10	7	2	2 small, 5 large	1 small, 1 large

Scenario 3 duplicates the number of potential treatment plants in relation to all the previous cases, but keeps constant the number of farms, collection centers and the length of the planning horizon with respect to the base case. The 16 possible treatment plants include the 8 ones associated with the base case. Provided the model has a bigger superstructure (504 versus 392 binary variables) with respect to the base case, it has the opportunity of finding a solution with a lower objective function value, or at least to reach the same solution as in the base case. The same solution as the base case one was reached in 4403 s, which indicates that in this case the new potential treatment plants do not lead to a solution improvement.

Along the same ideas, scenario 4 duplicates the number of potential collection centers in relation to all the previous cases, but keeps constant the number of farms, treatment plants and the length of the planning horizon with respect to the base case. As shown in Table 3, no optimal solution was obtained within 10000 s, but a solution having a 5% of relative gap has been reached in 9715 s. Given that the 40 potential collection centers include the 20 ones that correspond to the base case, a solution equivalent to the base case one, or better, was expected. In this case, the additional potential collection centers lead to an improvement in the base case solution. The new network comprises 5 extra collection centers, reducing the total discounted cost of the network due to savings in the transportation costs. In addition, the 5% gap indicates that further improvements can be obtained. Scenarios 3 and 4 allow concluding that the greater the number of potential nodes included in the superstructure, the greater the chances of obtaining good quality solutions. As expected, the increase in the number of binary variables demands an additional computational effort.

Scenarios 5 to 10 take into account the same superstructure as in the base case, but propose disturbances in different parameters to test the sensibility of the model to the changes. Scenarios 5 and 6 perturb the generation of empty containers from farms. In the first case, the generation of the base case is reduced by 50% in period 3, simulating an epoch with a reduced usage of agrochemicals due to changes in climatic conditions (drought). On the other hand, scenario 6 considers a gradual decrease in the generation of empty containers, in the same proportion for every farm, starting from period 3 up to the end of the planning horizon.

The optimal solution corresponding to scenario 5 was reached in 3489 s of CPU. It has the same facilities (see Fig. 1) identified in the base case solution. However, in this perturbed scenario two of the collection centers do not operate in period 3. The facilities that work in this period are the ones shown in Fig. 3. In turn, the optimal solution associated with scenario 6 was reached in 1634 s of CPU. It comprises six collection centers, one less than the base case solution. The reduction of facilities is due to the fact that fewer empty containers are generated along the planning horizon.

Scenarios 7 and 8 disturb the transportation cost, by proposing an increase of 10% and 20%, respectively. The structure of the solutions that have been obtained in both cases is the same as the one reached for the base case. Nevertheless, the total discounted cost of the network is higher due to the rise in transportation costs. These results show that the increments in the transportation costs are not yet enough to produce a modification in the network topology.

Finally, scenarios 9 and 10 disturb the installation costs of both types of facilities, by proposing an increase of 10% and 20%, as compared to the ones of the base case,

respectively. The optimal solution corresponding to scenario 9 was reached in 1308 s of CPU, whereas the one of scenario 10 required 2489 s of CPU. In both cases, the structure of the solution that was obtained is the same as the one associated with the base case. As expected, the total cost of the attained networks exhibit an increase, due to the rise in the installation costs of the facilities. Similarly to what happened in scenarios 7 and 8, the augmentations in the installation costs are not yet enough to produce a modification in the number and capacity of those facilities to be installed. As already presented, the base case solution has as its main cost components the installation and transportation ones, with a participation of 56.6% and 18.17%, respectively. In turn, the solution of scenario 9 has the following cost participation: 60.33% corresponding to installation costs and 17.8% to transportation ones. These percentages change to 61.4% and 16.7% in the case of the solution of scenario 10.



Fig. 3. Solution associated with scenario 6, showing the facilities that operate during period 3: Five collection centers (red dots) and two treatment plants (black squares).

6 Concluding remarks and future work

An MILP model for a multi-period reverse logistics network design problem has been presented. It takes into account several features that become relevant in supply chain configuration problems, such as: multi-period consideration, a three echelon network, discrete sizes for two facility types, minimum and maximum capacities for each of the available sizes of such facilities, as well as facilities that may have been already installed. In addition, the model considers variable costs per unit processed in the treatment plants, fixed operational costs and installation costs for all the available sizes of each facility type. Transportation costs only consider the distance traveled and omit the load of the vehicles, assuming that most of the trips are made with less than the maximum allowed load.

In order to reduce the computational load, a relaxation approach has been proposed. It rendered significant reductions in the CPU times without degrading, in any case, the quality of the attained solutions.

The model has been tested under various scenarios to analyze scalability and sensitivity issues. The obtained results have been satisfactory. Nevertheless, further testing will be done in the future to better study these aspects. For instance, a time horizon

with periods of shorter duration and a superstructure with more nodes will be tackled. In addition, the solutions will be evaluated under more demanding conditions of change in the model parameters. This would allow to better understand the tradeoffs between installation and transportation costs. Finally, the incorporation of environmental and social objectives, in addition to the economic ones, will be pursued in the future. This will naturally lead to a multi-objective formulation.

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Prefacio

Simposio Industrial ICPR-Americas 2020

Este volumen incluye los artículos presentados en el SIMPOSIO INDUSTRIAL de la "*Xth International Conference of Production Research-Americas*" (ICPR-Américas 2020), realizado en forma virtual en Bahía Blanca, Argentina del 9 al 11 de diciembre de 2020. Este Simposio fue organizado por un comité organizador local de la ciudad de Bahía Blanca y fue auspiciado por la *International Foundation of Production Research* (IFPR). El Simposio Industrial fue un evento complementario del ICPR-Americas destinado a miembros de la industria. En el mismo se presentaron y expusieron trabajos de índole práctica, referidos a las problemáticas en las que ellos mismos participan y los proyectos mediante los cuales abordan y resuelven dichos obstáculos. Los miembros de la industria que participaron del Simposio presentaron especialmente:

- Los problemas con que deben lidiar en la práctica cotidiana.
- El abordaje de los mismos a partir de proyectos de mejora e innovación que hayan implementado o estén implementando.

Los/as autores/as del Simposio Industrial participaron de la conferencia internacional, al igual que los/as autores/as del Congreso Académico. La audiencia y participación durante la presentación de los trabajos del Simposio Industrial contó con amplia asistencia de parte de los autores académicos, dando lugar a un debate que enriqueció recíprocamente a todos los participantes. En el acto de Apertura, los/as autores/as del Simposio Industrial recibieron las palabras del Prof. Luis Quezada de la Universidad de Santiago de Chile, presidente de IFPR. El desarrollo del Simposio Industrial superó ampliamente las expectativas, al contar con 17 trabajos presentados y expuestos por miembros directos de empresas del medio local, regional e incluso con participación de empresas extranjeras. Los trabajos recibidos fueron evaluados y analizados por los miembros de los distintos comités. Por su parte, el comité organizador del Simposio se encargó de toda la organización del evento, desde la concepción y estructuración del mismo -este Simposio fue la primera edición del mismo en el marco del ICPR-Americas-, la difusión, la gestión de los recursos y su administración para hacer posible el evento. También fueron los encargados de la edición de esta parte del Proceeding de ICPR-Americas 2020, titulada: "Simposio Industrial ICPR-Americas 2020".

Finalmente, sólo nos resta agradecer a todos/as los/as participantes, ya que confiaron en la organización de este evento para asistir y compartir sus conocimientos. Y también agradecer a los Sponsors, especialmente a la Universidad Nacional del Sur, en particular a los Departamentos de Ingeniería y Matemática, así como a la Secretaría General de Ciencia y Tecnología, por el apoyo brindado para la realización del evento.

Marzo 2021

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Índice de Satisfacción de Proveedores

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Reseña

Transportadora de Gas del Sur S.A. (TGS) es una empresa argentina, que nació en 1992. La compañía realiza 4 actividades principales:

- Transporte de gas natural: es la compañía más importante de Latinoamérica, opera con eficiencia y calidad más de 9.200 km de gasoductos propios, brinda un servicio público desde el sur y oeste de Argentina hacia los centros urbanos. Transporta más del 60% del gas consumido por los argentinos.
- Midstream: Desarrolla servicios a las empresas productoras de petróleo y gas natural en la provincia del Neuquén. En 2019, finalizó la construcción de un gasoducto y una planta de acondicionamiento en Tratayén, Vaca Muerta, que permite llevar el gas de la cuenca a los gasoductos troncales, transformándose en el primer midstreamer de Vaca Muerta.
- Telecomunicaciones: A través de su empresa, Telcosur, brinda servicios de telecomunicaciones en las regiones productivas más importantes del sur y oeste del país, pero también a nivel regional.
- Producción de líquidos del gas natural: en la ciudad de Bahía Blanca, realiza el procesamiento, almacenaje y despacho de butano, propano, etano y gasolina, a través del Complejo Gral. Cerri y la Planta Galván, desde donde se hace el despacho de líquidos a través de camiones y buques.

Para realizar estas actividades, TGS cuenta con 1.100 colaboradores, ubicados en oficinas administrativas, 33 plantas compresoras en las 7 provincias donde desarrolla sus actividades, 3 plantas de acondicionamiento en Neuquén y 2 instalaciones en Bahía Blanca.

Posee 9.231 km de gasoducto con una capacidad firme de transporte de 85 millones de metros cúbicos/día, con 780.000 HP de potencia instalada.

Su capacidad de procesamiento es de 47 millones de metros cúbicos/día, lo cual hace que sea el segundo procesador de gas natural en la Argentina.

Problemática detectada

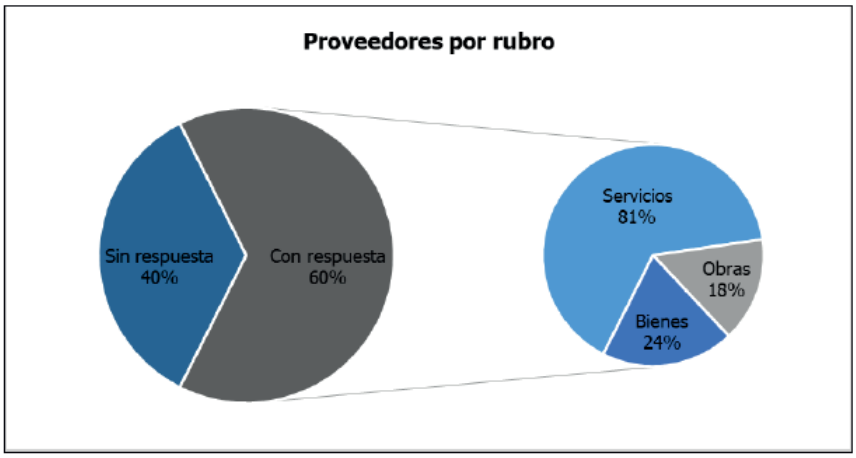
TGS se relaciona con una importante cartera de proveedores y contratistas. En su gran mayoría, empresas pymes de servicios, de fabricación y venta de repuestos, e insumos varios. Sin embargo, con el objetivo de atender las necesidades de sus proveedores y contratistas, TGS necesitaba una herramienta que le permitiera fortalecer sus vínculos comerciales. Realizaban consultas directas, pero necesitaba establecer un criterio metodológico de evaluación y mejora continua.

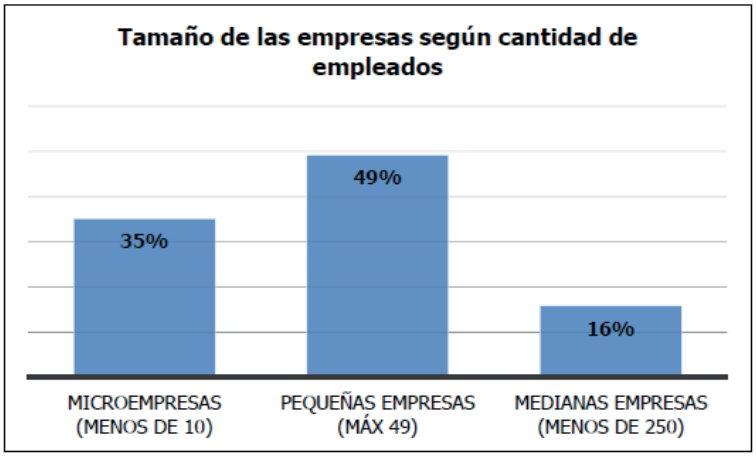
Solución implementada

TGS, en alianza con la UIBB, a través de su Centro de Estudios Económicos, diseñaron un Índice de Satisfacción de Proveedores, que permita medir el grado de satisfacción de los proveedores y aplicar medidas de mejora continua.

El primer paso, consistió en organizar una base de información de proveedores con el objetivo de actualizar los datos de la empresa.

Luego, como prueba piloto, se tomaron los 100 proveedores más importantes de la ciudad de Bahía Blanca y la región y se los dividió en tres grandes grupos: Servicios, Obras y Bienes.





Dichos proveedores debieron responder un cuestionario online, donde se consultó por los siguientes atributos:

- Comunicación: se evaluó la calidad de la comunicación.
- Procesos: los proveedores con acceso a planta evaluaron los procedimientos de la empresa.
- Atención y asesoramiento: la calidad de atención y asesoramiento.
- Resolución de problemas: respecto a la facilidad de resolución de problemas.
- Ejecución: desarrollo de los trabajos en la planta industrial.
- Proceso de pago: fluidez del proceso administrativo.
- Desarrollo de proveedores: se consultó respecto al rol de TGS y la contribución al desarrollo de la cadena de valor.

Para cada atributo, se utilizó una escala de valoración numérica desde el valor 1 (Muy Insatisfecho) al valor 5 (Muy Satisfecho). Un primer procesamiento de las respuestas, permitió obtener un grado de satisfacción por cada atributo relevado.

Posteriormente, se procedió a cruzar las variables con el objetivo de maximizar el análisis. De esta manera, se visualizará el grado de satisfacción, pero vinculando las respuestas, detectando y agrupando las distintas opiniones.

Los resultados de cada atributo se cruzaron con el rubro, la antigüedad de la empresa y el vínculo con TGS, el tamaño de la empresa y el área de TGS.

Este análisis, permite identificar las fortalezas y oportunidades en la relación con proveedores y contratistas y sus características, mejorando el vínculo comercial.

Finalmente, se calculó el Índice de Satisfacción de los Proveedores de TGS. El procedimiento consistió en tres etapas:

a) Selección de preguntas: consistió en elegir, de cada sección del cuestionario, aquellas preguntas consideradas claves para monitorear el

índice, es decir, cuya respuesta fuera fundamental para saber si mejora o no la satisfacción de los proveedores.

b) Ponderación de secciones y preguntas: consistió en darles un peso relativo tanto a cada sección del cuestionario como a las preguntas elegidas dentro de ellas, a fin de resaltar las más importantes y minimizar las superfluas en el cálculo del índice.

c) Cálculo y obtención del resultado: consistió en una operación matemática sencilla denominada suma ponderada, de acuerdo a las preguntas elegidas en a) y ponderadas en b).

Resultados obtenidos:

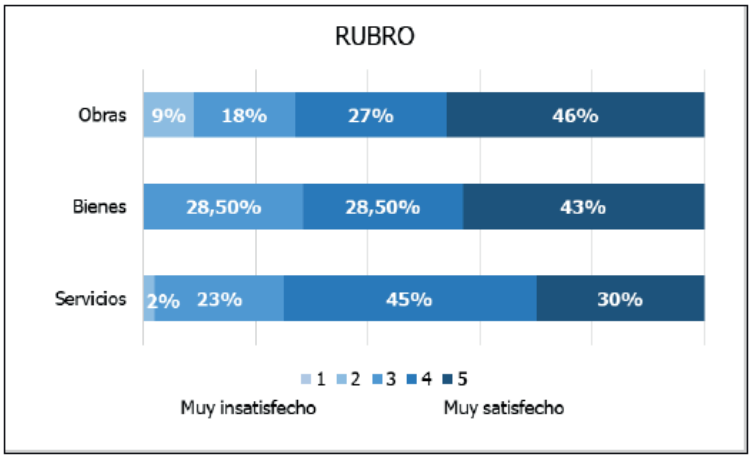
El cálculo de la línea de base del Índice de Satisfacción de Proveedores de TGS realizado en el mes de abril del año 2019 arrojó un valor de referencia de 209,4 puntos. La medición periódica del índice, permitirá monitorear si las acciones correctivas implementadas por la empresa tienen efectos positivos, negativos o neutros.

A continuación, se presentan los principales resultados del análisis de cruce de variables:

EJES	CLASIFICACIÓN
Rubro	Bienes Obras Servicios
Antigüedad de la empresa	Mayor a 10 años Entre 6 y 10 años Menor a 5 años
Antigüedad como proveedor	Mayor a 10 años Entre 6 y 10 años Menor a 5 años
Tamaño de la empresa	Medianas empresas (menos de 250) Pequeñas empresas (máx. 49) Microempresas (menos de 10)
Área	Mantenimiento Ingeniería y Obras Ss. generales Seguridad y Medio Ambiente Otro Productos Laboratorio Comunicaciones Vigilancia Servicio Operativo

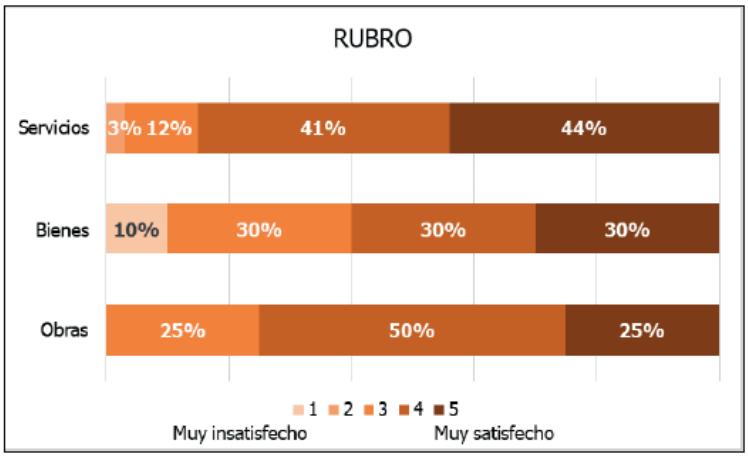
Comunicación

Grado de satisfacción respecto a la experiencia de alta como proveedor de TGS.



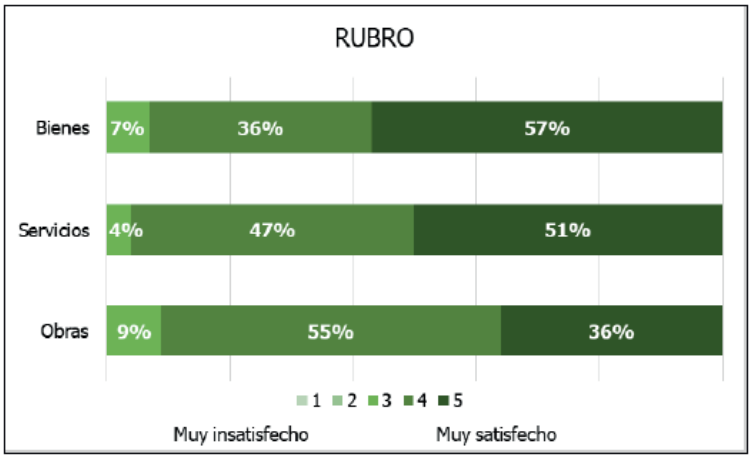
Procesos

Grado de satisfacción con el proceso de acceso al lugar del trabajo en la planta.



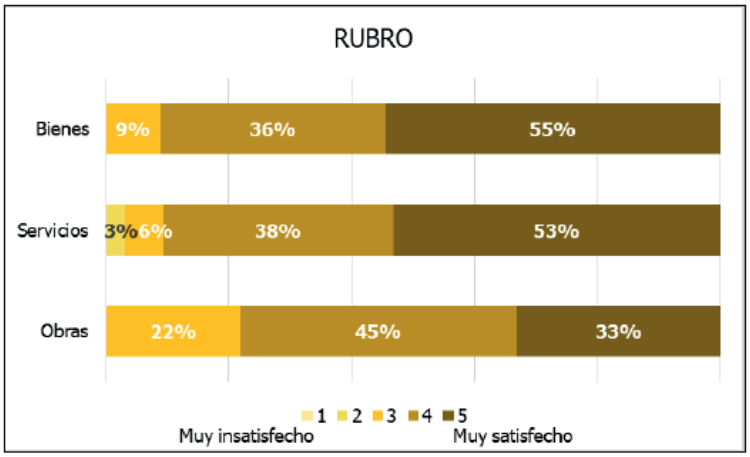
Atención y asesoramiento:

Grado de satisfacción con la calidad profesional del personal de TGS.



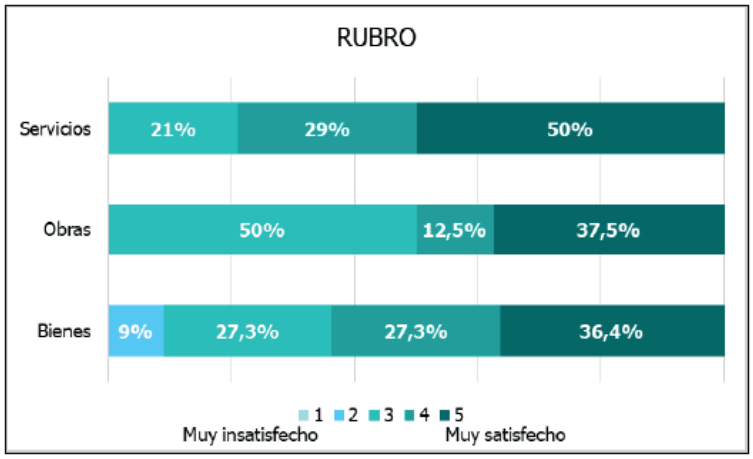
Ejecución:

Grado de satisfacción con las condiciones de seguridad que brindaron al personal durante la ejecución de los trabajos.



Proceso de pago:

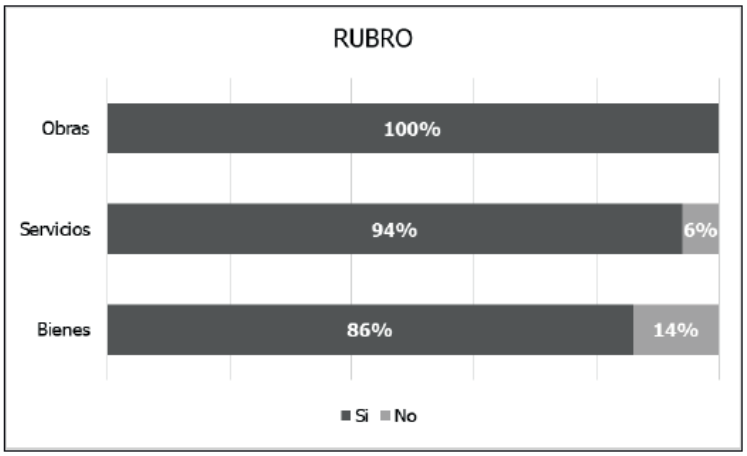
Utilización y grado de satisfacción del nuevo portal de carga y pago de factura.



Desarrollo de proveedores:

Es un dato significativo: la mayoría de las empresas afirma haber tenido un crecimiento a partir de su relacionamiento con TGS. Esta afirmación proviene del 100% de los proveedores para el caso del rubro "Obras", las empresas entre "6 y 10 años" de antigüedad, las Microempresas y las áreas Servicio Operativo, Vigilancia, Comunicaciones, Laboratorio y Servicios generales.

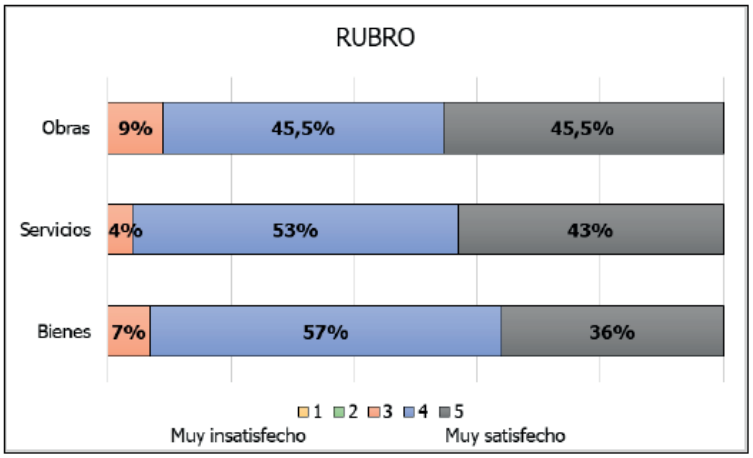
TABLA 1. Crecimiento de la empresa a partir del relacionamiento con TGS.

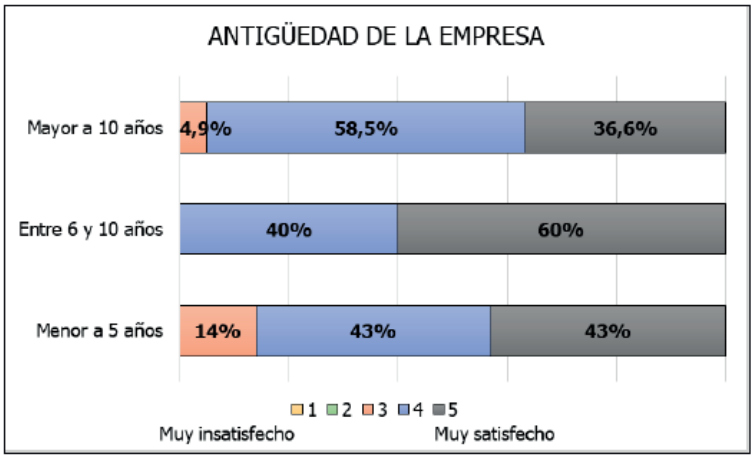


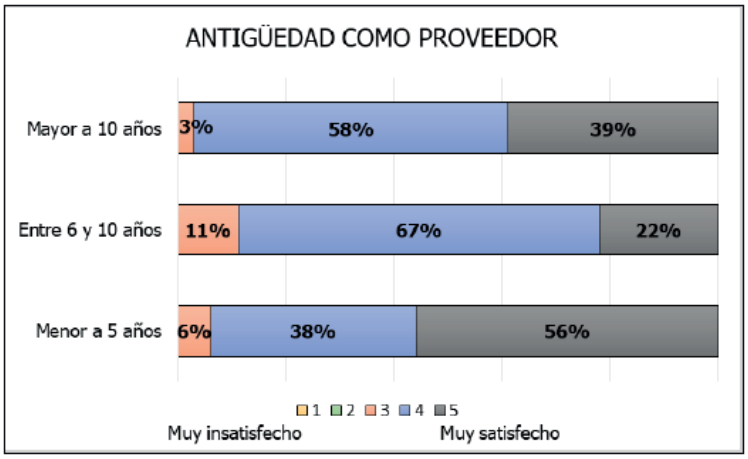
Satisfacción general:

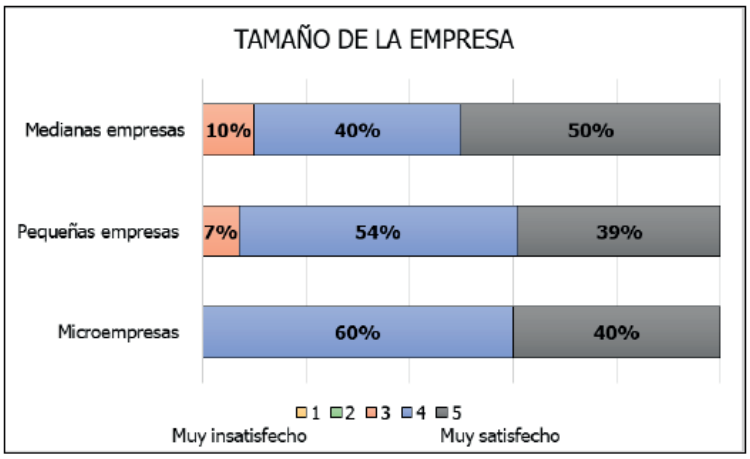
Respecto de la satisfacción general de los proveedores, se puede destacar que no hay calificaciones para la sección más baja de la escala (niveles 1 y 2). Los mayores

porcentajes se encuentran en los niveles 4 y 5, lo que es algo muy positivo para la empresa, ya que independientemente de los inconvenientes específicos los proveedores se muestran satisfechos con su relación comercial.









Comentarios finales:

El caso analizado permitió conocer la vinculación entre una gran empresa (TGS), sus pymes proveedoras y la Unión Industrial. Sin dudas, el Índice de Satisfacción de los Proveedores de TGS tiene aspectos positivos, desde su diseño, por parte del Centro de Estudios Económicos de la UIBB, hasta su análisis en el equipo de trabajo. Asimismo, la interpretación de los resultados y la voluntad de la empresa por mejorar el relacionamiento con sus proveedores y contratistas, conociendo sus necesidades y problemáticas.

Auditoría integral para una administración eficiente

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bertonialejandro@gmail.com

Breve reseña de la empresa

Devic S.R.L. es una empresa familiar constituida en el año 1986 que comenzó sus actividades brindando servicios de herrería de obra, en el barrio de Villa Mitre de la ciudad de Bahía Blanca. A lo largo de los años, se fue expandiendo y diversificando las actividades. En 2002 se constituyó como SRL, viéndose con la necesidad de agrandar las instalaciones. Por tal motivo se ha trasladado a un predio propio en el Parque Industrial de Bahia Blanca. Hoy en día, a 34 años de su nacimiento, la empresa cuenta entre sus diversas unidades de negocios, con 110 empleados en la nómina, y presta todo tipo de servicios industriales principalmente en el Polo Industrial de Bahía Blanca, el cual ha sido el principal nicho de mercado durante varios años.
En los últimos años la empresa se ha diversificado y ha emprendido el negocio de fabricación y montaje de aberturas de aluminio, incursionando también más recientemente en la elaboración de hormigón. Con estos dos últimos negocios la empresa ha expandido su clientela a diversos sectores de la ciudad de Bahía Blanca y la zona, ya que anteriormente se concentraba sólo en grandes industrias del Polo.

Problemática detectada

En cuanto a una de las problemáticas que se vio afectada la empresa, se encuentra relacionada al proceso administrativo. El origen del mismo fue el crecimiento de la empresa, la expansión de las unidades de negocio, la cantidad de personal y las nuevas actividades. Todos estos factores han generado que la necesidad de información y el procesamiento de la misma sean cada vez más complejos, potenciado en cuanto a que se trata de un rubro (el administrativo-contable) en cual los directivos que la componen no son idóneos (como lo son, por ejemplo, en el aspecto técnico-productivo).

Esta falencia fue detectada por diversos motivos:

- Se poseía información desactualizada, saldos de clientes, saldos de proveedores, informes de gastos, detalle de facturas pendientes de cobro,

cheques diferidos a pagar, y otros tipos de informes necesarios para gestionar las finanzas de la empresa.

- Había demoras en respuesta a requerimientos de distintas entidades bancarias, en el armado de las carpetas necesarias para calificar, informes solicitados por el estudio contable, y otros requerimientos de los propios directivos.
- Se detectaba cierta duplicidad de tareas en el sector administrativo, como por ejemplo en la emisión de facturas que se realizaban por medio de la página web de AFIP y luego se cargaba al sistema de gestión, se realizaba un cálculo de percepciones y retenciones que luego era validado por el sistema de gestión, se llevaba un Excel a mano con la composición de saldos de clientes que también se cargaba en el sistema, entre otras.
- No se utilizaban todas las herramientas del sistema de gestión administrativo que estaban disponibles, ya que mucha información se manejaba en hojas pasadas a mano o en listados en Excel; como se indicó anteriormente de saldos de clientes, emisión de cheques por medio del sistema, detalle de gastos por concepto, entre otras.
- Había determinados procesos productivos que se querían plasmar en la administración de una forma distinta, con mejoras informáticas que se venían realizando de manera manual; así era el caso de las herramientas o insumos que se retiraban del pañol, o las horas de trabajo que se afectaban a órdenes de trabajo; se realizaba todo a mano y luego se trasladaba a un sistema informático, que ocupaba gran parte del tiempo del personal administrativo.

Solución implementada

Al notarse estas cuestiones y verse imposibilitados de solucionarlo por medios propios, ya sea por parte de los directivos o por los recursos humanos propios de la empresa, se decidió buscar una solución en una consultora externa, planteando que la empresa se encontraba con estos inconvenientes y necesitaban una solución al respecto. Por ello, se recurrió a la Unión Industrial de Bahía Blanca, como entidad gremial empresaria a la que pertenece Devic S.R.L. para buscar una solución al respecto, donde encontró que hay una diversidad de departamentos especializados en estos temas.

Resultados obtenidos

Desde el Departamento de Políticas Tributarias se propuso al respecto realizar una auditoría integral de la administración, mediante un plan de trabajo claro y preciso, con la finalidad de:

- Detectar todas las posibles falencias que se encontraría atravesando la empresa en cuanto al circuito administrativo.
- Informar las consecuencias que tendrían aparejadas las mismas.
- Plantear posibles soluciones para corregir dichas falencias.

La auditoría fue muy satisfactoria en cuanto a:

- Errores detectados en el proceso administrativo, que implicaban diferencias en liquidaciones impositivas, los cuales sirvieron para mejorar de allí en adelante para no repetirlos, con lo cual se ahorraron recursos propios.
- Mejoras en los procesos del sistema de gestión administrativo, ya que se implementaron todas las herramientas del software informático que se poseía pero que se encontraba en desuso por falta de implementación e instrucción al personal administrativo, mejorando así los registros y la disponibilidad de datos.
- Mejoras en los procesos administrativos en cuando a evitar duplicidad de tareas y sintetizar ciertos pasos que eran improductivos, generando una eficiencia en los recursos humanos permitiendo afectar una mayor disponibilidad de los mismos a otras tareas.

La consultoría no solamente culminó con un informe completo de los procesos de auditoría aplicados, las falencias detectadas y las formas de corrección de los mismos, sino que también se instruyó al personal administrativo de cómo llevar a cabo las mejoras propuestas.

Por último, y en base a los buenos resultados que se obtuvieron, se encargó a los consultores la implementación de un nuevo sistema informático para la obtención de la información del sector productivo. Para esto se contactó a una firma desarrolladora que se encargó de plasmarle todas las necesidades que debía satisfacer en cuanto a procesos e información que debía brindar. Por otro lado, se encargó de realizar las pruebas de funcionamiento del sistema, una vez que el mismo fue desarrollado; y también llevo a cabo la capacitación al personal de Devic S.R.L. para la utilización del mismo.

Comentarios finales

Es normal que muchas empresas se encuentren sumidas en el día a día y no dispongan de tiempo para un análisis exhaustivo de sus procesos, tanto técnicos como administrativos. En otras ocasiones, las firmas cuentan con tiempo pero no con recursos económicos.

En este sentido, se destaca la visión y voluntad de los directivos de hacer la auditoría integral, y la respuesta obtenida por parte de la gremial empresaria a la que recurrieron, ya que pudo ofrecerles un servicio profesional y eficiente.

Luego de dichas modificaciones y mejoras, los directivos evaluaron la necesidad de contar con un profesional idóneo en cuestiones administrativas que pudiera mantener eficiente de manera continua los procesos administrativos. Con lo cual, se contrató a un profesional idóneo en la materia dedicado exclusivamente a realizar estos trabajos de organización administrativa interna.

Es muy importante notar que el costo económico de una auditoría integral de estas características, redunda en el corto plazo en ahorros que claramente superan el gasto efectuado. La eficiencia de un sistema administrativo-contable es clave para un manejo integral de los recursos de la firma.

Hoy en día, la empresa se encuentra más que satisfecha en cuanto al procesamiento de la información y de la organización del sector administrativo; quitando de encima la preocupación a los directivos en cuanto al mismo.

Mejora en la competitividad empresarial: acciones implementadas

Marcela Contreras, Luis Contreras y Emily Martínez

Plumas, Bahía Blanca, 8000, Argentina

Breve reseña de la empresa

Plumas es una empresa textil familiar que inició sus actividades en el año 2006 en un garaje de 25 metros cuadrados en la localidad de Bahía Blanca, bajo la dirección de los hermanos Marcela y Luis Contreras. En sus inicios se dedicó a la producción de prendas de noche (sacos, vestidos, remeras, soleras) y ofreciendo sus productos en sus locales. Estas prendas se confeccionaban para marcas del Bahía Blanca Plaza Shopping y para locales del centro comercial de la ciudad. En sus inicios compraban tela por metro y producían un 5% de su capacidad actual. Al dedicarse a confeccionar prendas de moda actual, la empresa no podía contar con grandes volúmenes de stock, ya que la moda cambia permanentemente y muta en cuestión de días.

En términos de superficie y capacidad, en el año 2012 ocupó toda la propiedad donde estaba radicada (100 metros cuadrados), triplicando su capacidad productiva y comprando tela por rollos. En 2018 suma un galpón adicional de 75 metros cuadrados. En la actualidad cuenta con un área total de 200 metros cuadrados más un depósito.

Con el paso del tiempo, la empresa redefinió su orientación en la fabricación de indumentarias y comenzó a dedicarse a la producción de ropa deportiva y ropa escolar, centralizando así sus insumos y utilizando mayoritariamente el color azul.

Posteriormente, Plumas redefinió nuevamente su producción fabril y comenzó a dedicarse a la confección de indumentaria para empresas (pantalones cargo, camperas, camisas, chombas). Asimismo, Plumas brinda a sus clientes una atención personalizada, ya que, si bien cuenta con productos estándar, también confecciona prendas a pedido y especializadas.

Problemática detectada

Al comenzar a vender artículos en grandes volúmenes, la empresa se vio en la necesidad de especializarse y adquirir maquinaria más específica que le permitiera abastecer su elevada demanda, surgiendo así también la necesidad de reducir sus costos de producción.

Por otro lado, a medida que las ventas se incrementaban, comenzaron a formarse dos "cuellos de botella". Uno se debía al poco espacio con que contaba la empresa para colocar los grandes volúmenes que se producían, mientras que el otro se debía a que la mesa de corte utilizada no resultaba lo suficientemente extensa como para lograr los elevados niveles de producción requeridos.

Por otra parte, un inconveniente que era común a todas las empresas textiles de Bahía Blanca era la disminución de la mano de obra capacitada en máquinas industriales, ya que la empresa establecida en la ciudad dedicada a la capacitación de mano de obra a nivel industrial (Torello) decidió cerrar y dar por caducadas sus actividades.

Finalmente, un problema con el que se encuentran todos los proyectos en Bahía Blanca al momento de iniciar sus actividades es la competencia existente con la ciudad de Buenos Aires, ya que, al hallarse las empresas bahienses a una distancia de 700 kilómetros de sus proveedores, se generan elevados costos en los insumos de producción debido al costo involucrado en el traslado de los mismos.

Solución implementada

Con respecto a la necesidad de contar con maquinaria especializada, la empresa adquirió máquinas computarizadas. Estas máquinas cuentan con motor servo y luces led, y consumen energía sólo cuando el operario se encuentra utilizándolas, a diferencia de máquinas industriales más antiguas que consumen energía por el simple hecho de estar encendidas, aunque el operario no se encuentre utilizándolas.

Con respecto al "cuello de botella" generado por el escaso espacio, la empresa logró trasladar el taller a un galpón de mayor superficie, mientras que, en cuanto a la restricción generada por las dimensiones de la mesa de corte, Plumas adquirió una mesa más amplia a la que se le adhirió un carro con ruedas en la parte superior, el cual va desplazándose de un lado a otro con los rollos de tela. Por otro lado, al trasladar el taller a un lugar más espacioso, la mesa de corte también se trasladó allí, ya que anteriormente la mesa se encontraba a dos cuadras de la fábrica.

En cuanto a la necesidad de mano de obra capacitada, junto con gente del Grupo Textil de la UIBB e interactuando con el Consejo Escolar y con la Municipalidad de Bahía Blanca, se formó un curso en el cual personal capacitado en máquinas industriales continúa con la formación de mano de obra profesional, siendo declarado el mismo de interés municipal. El curso se denomina Confeccionando Futuro.

Por último, acerca de la gran competencia que ejerce la ciudad de Buenos Aires, cuando la empresa Plumas se dedicaba a la confección de prendas de noche, realizaba periódicamente viajes a dicha ciudad con el fin de observar las tendencias en moda existentes en los centros comerciales de La Salada, Flores y Once (su competencia en aquel momento), y, de este modo, poder ofrecer al mercado productos diferenciados y con un mayor valor agregado. Luego, al dedicarse a la producción de ropa escolar y

de indumentaria para empresas, Plumas comenzó a comprar grandes volúmenes de escasos insumos, generando así la centralización de los mismos. Finalmente, la atención personalizada que la empresa brinda a sus clientes es la gran diferencia que posee con respecto a sus competidores.

Resultados obtenidos

En primer lugar, las máquinas computarizadas generaron un 30% de reducción de costos energéticos debido al menor gasto eléctrico que conllevan.

En segundo lugar, el traslado del taller a un lugar más amplio y la adquisición de una mesa más extensa, permitió el aumento de la producción y el crecimiento de la empresa, lo que generó un aumento de un 10% en la capacidad de corte, disminuyendo el costo unitario del corte. A su vez, el desplazamiento de la mesa de corte al nuevo taller generó un aumento de la productividad y un ahorro del 10% de los costos por la disminución de los traslados. De igual modo, la adhesión de un carro con ruedas a la mesa de corte permitió una reducción de costos en mano de obra (50% de la encimada), ya que anteriormente, en la mesa se necesitaban dos operarios, mientras que ahora se necesita solamente uno.

Por último, la centralización de los insumos por parte de la empresa también permitió una disminución de los costos debido a los grandes volúmenes de compra y permitió un aumento de su competitividad en el mercado. Esto permitió lograr además crédito con los proveedores, brindándole oxígeno a las finanzas de la empresa, que pudo afrontar grandes licitaciones apalancándose con sus proveedores.

Todos estos ahorros de costos y mejoras en la productividad se traducen en ganancias de competitividad y se resumen en la siguiente tabla:

Problemática	Acciones Implementadas	Resultados
Necesidad de adquisición de máquinas especializadas para abastecer la elevada demanda	Adquisición de máquinas computarizadas	Reducción de un 30% en costo de energía
	Traslado del taller a un espacio más amplio y adquisición de una mesa de corte más extensa	Aumento de un 10% en la capacidad de corte
"Cuellos de botella" generados por el escaso espacio y por tener una mesa de corte pequeña	Traslado de la mesa de corte al nuevo taller	Reducción de un 10% en costos de traslados

	Adhesión de un carro con ruedas a la mesa de corte	Reducción de un 50% en mano de obra para la encimada de las telas
Elevados costos generados por el traslado de los insumos desde la ciudad de Buenos Aires	Realización de grandes compras de insumos, obteniendo créditos con los proveedores que permiten afrontar grandes licitaciones apalancándose con los mismos	Reducción de los costos por el traslado de los insumos, generando un ahorro que se puede direccionar en otras áreas de la empresa

Comentarios finales

La mejora o pérdida de competitividad de las empresas puede analizarse desde las perspectivas micro y macroeconómicas. En muchos casos ambas vertientes funcionan potenciadas y en otras contrapuestas. Se potencian en sentido positivo cuando buenas medidas macroeconómicas generan un incentivo a mejorar puertas adentro, y entre ambas logran mejorar la competitividad. En cambio, en otros casos, ambas tienen una función compensadora de la pérdida de competitividad generada por la otra vía. Este es el caso en que los gobiernos deben tomar medidas sectoriales (por ejemplo, créditos subsidiados, intervenciones de precios, limitaciones al comercio exterior) cuando las empresas no son eficientes. O bien, cuando las firmas deben cambiar estrategias y reinventarse frente a un contexto macro adverso (por ejemplo, por falta de crédito, inestabilidad en el mercado cambiario, inflación alta).

El caso relatado de la empresa Plumas se puede encuadrar en este último ejemplo y no difiere demasiado de la situación que atraviesan numerosas pymes, tanto del rubro textil como de otros. Se rescata de este caso la capacidad de reaccionar a tiempo y cambiar de estrategia, a la vez que apoyarse en un grupo de pares para la búsqueda de soluciones conjuntas.

Confeccionando Futuro: curso técnico con función social

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Breve reseña

Creado desde el departamento de los Jóvenes Empresarios de la Unión Industrial en el año 2012, GRUPO TEXTIL es un espacio que reúne a las empresas, ya sean fábricas o talleres del área textil de Bahía Blanca y la zona de influencia, con el objetivo de establecer políticas estratégicas para lograr el crecimiento competitivo como así también aumentar las ventas y reducir diferentes costos en materia prima, mano de obra calificada, logística de distribución y comercialización, entre otros objetivos.

Asimismo, cumple una función social brindando cursos y capacitaciones, con el objetivo de que los alumnos aprendan y adquieran diversos conocimientos para que en un futuro puedan contar con un emprendimiento personal.

El objetivo del grupo es nuclear, representar y promover el área textil con el fin de incentivar el desarrollo de fábricas y talleres en nuestra ciudad y la región, generando valor agregado y puestos de trabajo, fomentando la innovación, competitividad, inversión y desarrollo sustentable de la economía local y regional, con un compromiso en el cuidado del medio ambiente y la responsabilidad social empresaria. El mismo tiene como espacio físico la casa matriz de la Unión Industrial de Bahía Blanca.

Algunas de las empresas que forman parte del mismo son: Plumas. Fábrica de indumentaria, Sueño Austral, Bordatech Bordados, Papelera Morus, Serigrafía Gómez, El Vaticano.

Problemática detectada

La problemática surgió del diálogo entre un conjunto de industriales de distintos rubros que tienen en común la constante necesidad de mano de obra calificada y/o especializada. En otras palabras, un grupo de empresarios de la ciudad manifestaron la persistente escasez de oferta de mano de obra capacitada para cubrir puestos en la industria textil.

Muchos operarios y/o emprendedores solo contaban con conocimientos de manejo de máquinas familiares que en muchas ocasiones quedaban obsoletas para ciertos

trabajos, por lo tanto, era necesario otorgarles la posibilidad de capacitarse con máquinas industriales para que puedan progresar.
Individuos que buscan emplearse y no están capacitados = exceso de oferta que se busca capacitar
Empresas que requieren de mano de obra calificada = demanda insatisfecha que se busca cubrir

Solución implementada

Entre las distintas empresas que componen Grupo Textil, la UIBB y el Consejo Escolar se creó el curso "CONFECCIONANDO FUTURO" como respuesta a la necesidad de mano de obra calificada, la falta de emprededorismo y la ausencia de capacitación en los operarios del rubro textil. El mismo se concretó conjuntamente con el Centro de Formación Profesional Nro. 404 de General Cerri.

Se trata de una capacitación gratuita en la que los alumnos adquieren conocimientos en confección industrial de textiles realizando sus prácticas en el taller textil que cuenta con máquinas industriales. Con esto se busca que adquieran la capacidad de diseñar con autonomía sus confecciones para que en un siguiente paso puedan comercializarlas y desarrollar su propio emprendimiento textil. Además, se realizan visitas a fábricas textiles para que los alumnos vivencien y experimenten el espíritu empresarial.

Por otro lado, se les brinda talleres de diseño, emprededorismo, y charlas de coaching de manera que conozcan las experiencias de otros. Asimismo, cuentan con un taller de administración de empresas que tiene como objetivo que el alumno que egresa sea capaz de realizar un presupuesto de su negocio, calcular sus costos, como así también tener una idea general de cómo funciona un monotributo y cuáles son los beneficios que este trae.

Las clases teóricas y prácticas son dictadas en las instalaciones de la UIBB. El dictado del curso dura un cuatrimestre, brindando dos cursos al año con un cupo máximo de 25 alumnos por curso. Las únicas condiciones para ingresar es ser mayor de 16 años y haber culminado la educación primaria.

Por otro lado y con el fin de incentivar a los emprendedores se implementaron línea de créditos con distintos bancos y la Municipalidad de Bahía Blanca. Se trata de créditos que no generan intereses en donde el cumplimiento del pago total del mismo habilita a adquirir un crédito mayor el siguiente año.

"CONFECCIONANDO FUTURO" funciona como un "mercado de trabajo" en donde los alumnos una vez capacitados y egresados del curso tienen la posibilidad de ingresar a las distintas fábricas y/o empresas que requieran de tal mano de obra.

Resultados obtenidos

El desarrollo del programa generó grandes oportunidades de desarrollo de emprendimientos a nivel local y formó mano de obra calificada para las empresas textiles con los egresados. Es decir, se creó un mercado de trabajo en donde personas que se encontraban desempleadas fueron capacitadas y lograron cubrir la demanda de mano de obra calificada insatisfecha de las distintas fábricas.

Esto no sólo otorga un ingreso al alumno y un beneficio a la empresa, sino que también cuando una persona es capacitada y logra crear algo por sí misma se siente empoderada. En este sentido, el individuo se siente capaz de independizarse y más útil. A su vez, cuenta con mayores habilidades para desarrollarse día a día y con esperanzas de progreso

De forma complementaria creó relaciones entre los integrantes del curso brindando la capacidad de apalancarse mutuamente con sus emprendimientos de forma conjunta, generando cooperativismo entre sí.

Tabla 1. Indicadores de los cursos CONFECCIONANDO FUTURO

Egresados en 6 años (dos cuatrimestres por año)	275
Alumnos que se asociaron formando grupo	6
Alumnos que obtuvieron crédito del municipio	1
Alumnos que adquirieron máquinas (con ayuda del Grupo Textil)	6
Alumnos que ingresaron a trabajar por el curso	5
Alumnos que realzaron prácticas	10
Alumnos que trabajan desde sus hogares	25
Alumnos que realizaron tutoriales Paso a Paso por TV	5

Cabe destacar que los casos contabilizados en esta tabla son aquellos de los que se tiene conocimiento, es decir, en varios ítems debe haber más alumnos, pero se desconoce el número ya que no se realiza un seguimiento personalizado.

Comentarios finales

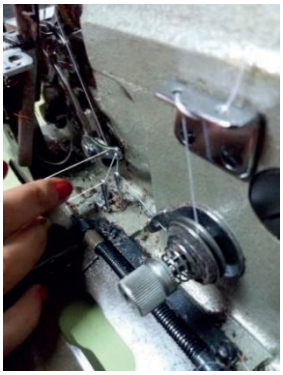
“CONFECCIONANDO FUTURO” lleva 6 años de continuidad y fue declarado curso de interés municipal. Además, tuvo participación en la bolsa de trabajo de la Municipalidad de Bahía Blanca, brindándoles capacitaciones a algunos de los inscriptos en la misma que se encontraban desempleados en ese momento.

Por otro lado y debido a la gran repercusión del curso en el área textil, cuatrimestralmente sólo logran llevar adelante el curso el 25% de los inscriptos, ya que por la capacidad de las instalaciones se debe poner un máximo de alumnos por cuatrimestre. Todo esto da cuenta de la gran potencialidad que tiene esta actividad.

Se refleja en esto la importancia de generar espacios para que personas que por distintas razones no pueden acceder a una educación secundaria, terciaria y/o universitaria tengan la posibilidad de contar con herramientas para desarrollarse y llevar a cabo su propio negocio sin una dependencia directa.

Documentos fotográficos









Modificación en el sistema de retornabilidad de envases de Coca-Cola

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Resumen

Los empaques retornables de vidrio y el llamado Ref-Pet (Refillable Pet) son claves dentro del portafolio de la compañía ya que ofrecen al consumidor una opción de consumo a un precio asequible, especialmente bajo condiciones económicas difíciles.

Sin embargo, la llamada "retornabilidad" presenta grandes desafíos, no sólo vinculados al consumidor y su proceso de compra, sino también dentro del llamado "Sistema Coca-Cola" que incluye un alineamiento entre la compañía, los embotelladores, la fuerza de ventas y el canal.

Entre algunos desafíos se destacan la complejidad operativa de producción de envases, la falta de incentivos para los integrantes del sistema, el retornable como experiencia de compra inferior y de baja calidad donde el comprador suele sentirse un "comprador de segunda", la baja practicidad del proceso de compra, envases desgastados y con apariencia de falta de higiene, entre otros.

Bajo este contexto nace un plan de reconversión del negocio, en el que se define un nuevo marco estratégico para la retornabilidad, alineando los elementos intervinientes en el sistema para ofrecer no sólo un producto asequible sino también una mejor experiencia de compra.

El trabajo pretende mostrar cómo impactó (e impacta) - particularmente en el área operativa de embotellado de la bebida - una de las acciones más significativas en esta nueva estrategia: la migración del envase serigrafiado (ACL) a envase genérico o multi-producto.

Palabras clave: Estrategia, envase retornable, multi-producto.

1 Situación histórica VS ideal

Los desafíos planteados en el resumen, sumados a una caída del consumo, hacen que la estrategia de Coca-Cola esté enfocada en reforzar los programas de retornables y la diversificación de las presentaciones es un punto clave.

Rediseñar el empaque retornable implica generar un cambio para resignificar su imagen y evitar ser percibido como de segunda categoría. Es importante generar esta conciencia desde las etiquetas y la calidad del envase y transmitirlo así a todo el sistema.

Se busca asegurar un nuevo diseño que permita por un lado el reposicionamiento del empaque para que luzca de calidad, tanto en vidrio como en plástico, y por otro,

que facilite la mecánica operativa en las plantas embotelladoras. Para esto último, la introducción de etiquetas de papel permite la flexibilidad operativa de producción frente a la demanda estacional de diferentes sabores. De esta manera se genera un empaque multi-producto que además da pie a la libre intercambiabilidad de envases.

Tabla 1. Principales impactos en las operaciones de las distintas áreas

	ACL (Applied Ceramic Label)	**Multi-producto**
Marekting	Imposibilidad de adaptar la imagen a situaciones concretas (ej: Navidad)	El arte de la etiqueta puede adaptarse fácilmente, según se requiera
	Las promociones quedan limitadas al color de la tapa (sin información alguna)	La etiqueta de papel puede contener la información y la imagen
Venta	El ACL sufre un desgaste que no es bien percibido en la góndola	El envase tiene una mejor imagen a pesar del desgaste del PET
	El comerciante devuelve los envases sin clasificar dentro de cajones	No es necesario que el comerciante clasifique los envases dentro de los cajones
Transporte	Los camiones sólo cargarán los envases del sabor que corresponda en cada caso	La carga de camiones es más eficiente
	Posible capacidad ociosa	No hay capacidad ociosa
Almacenamiento	Es necesario un proceso de clasificación de envases por sabor (líneas de sorting o personal exclusivamente dedicado a hacer la tarea manualmente)	Los envases se introducen en la línea tal como llegan desde el comercio
	Los envases vacíos deben almacenarse en estibas individuales (por sabor)	Las estibas de envases vacíos son únicas
	Mayor espacio utilizado en el depósito	Mejor aprovechamiento del espacio en el depósito
Embotellado	La clasificación manual de envases no es suficiente	No es necesaria la clasificación manual
	Cada equipo inspector de la línea de producción debe estar calibrado para cada sabor	Las variables de ajuste de los equipos se reducen significativamente
	Frecuentes incumplimientos de la planificación por falta de envases disponibles en planta	Envases siempre disponibles por mejor ciclo de retornabilidad
	Mayores tiempos entre cambios de sabores	Menores tiempos entre cambios de sabores

2 Situación actual

Una decisión estratégica de este tipo implica grandes desembolsos de dinero. El análisis sobre dónde, cuándo y cómo llevar a cabo la migración debió ser lo más detallado posible.

La planta de Bahía Blanca fue la elegida por Coca-Cola Andina para iniciar este cambio en 2017, y la manera de migrar el parque de botellas fue gradual. Actualmente, la proporción de envases llenados en ACL es del 20%. Pero en poco tiempo, los sabores de Fanta y Sprite (y más tarde Coca-Cola) serán envasados 100% en envase genérico debido a que la no renovación del parque serigrafiado hace que la calidad de las botellas que están en el mercado haya llegado a su límite inferior.

Si bien todo parece indicar que la introducción del nuevo envase es la solución a un gran número de limitaciones, en la práctica se observaron muchos desafíos, surgidos de la coexistencia del ACL y el multi-producto, a saber:

- La clasificación de envases se complejizó al incorporarse un nuevo grupo de botellas que, si bien es indistinto la etiqueta que tengan, deben separarse del envase con ACL por cuestiones operativas y logísticas.
- Se añadieron muchas más variables a los equipos inspectores (por imágenes), algunos de los cuales no fueron diseñados para tal fin, por lo que debieron parametrizarse adecuadamente o bien debió incrementarse la labor manual (ej: una etiqueta mal pegada puede ser interpretada como un objeto extraño, produciendo un falso rechazo)
- La frecuencia de lavado de filtros de la lavadora de botellas y la mantención general del sistema de extracción de etiquetas se incrementó casi un 100%, pasando de ser una tarea de mantenimiento planificado a un trabajo diario del operador de producción.
    - La máquina debió ser intervenida por el fabricante para aumentar el nivel de extracción de etiquetas.
- La etiquetadora pasó de ser un equipo prácticamente en desuso – únicamente se usaba en el formato de 2,5 L – a cumplir un rol fundamental en el proceso de embotellado.
    - La optimización en el uso del adhesivo de etiquetas fue motivo de un proyecto de mejora llevado adelante por supervisores y operadores.
    - Debió elaborarse un plan de capacitación de personal para garantizar la presencia de un titular en cada puesto de trabajo.
- Debió implementarse un sistema diferenciado de rotulación de pallets para garantizar que los dos tipos de envases lleguen por separado a los destinos en que no existe clasificación a la hora del retorno a planta.
- El reciclado del envase “clear” fue un punto muy positivo, pero también agudizó la inspección del envase rechazado en la línea y añadió varias tareas más al proceso de descarte –segregación, identificación y disposición final diferenciada -.

3 Conclusiones generales y particulares

Los envases retornables son clave dentro de un portafolio balanceado. Por un lado, ofrecen una opción de consumo asequible bajo condiciones económicas difíciles y por otro, asegurando una compra inteligente y ecológica. Funciona tanto como una herramienta de penetración y acceso para los segmentos económicos más bajos como así también para los más altos.

Dentro del portafolio, cumple la función clave de asegurar el ingreso, afianzar la frecuencia de consumo y permitir el escalamiento hacia productos de mayor tamaño.

Sin embargo, el camino del crecimiento de la retornabilidad en Argentina presenta muchos desafíos.

Es fundamental lograr una estrategia integral unificada y alineada a todo el sistema para generar un valor agregado diferencial para afianzar el camino de crecimiento en un contexto de negocios cada vez más dinámico y competitivo.

Los puntos mencionados en el apartado 2 (y varios otros) hablan de la complejidad que conlleva una decisión de este tipo cuando pretende realizarse a gran escala. Cuantas más áreas se vean involucradas en la decisión, mayor será la complejidad.

Es fundamental lograr una clara comunicación - entre las áreas y entre los distintos escalafones de una misma área - de todas las acciones surgidas del plan maestro, para minimizar la pérdida de tiempo en un proceso extenso por naturaleza.

4 Referencias

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Estudio del aumento de la capacidad de molienda en sistemas de producción de alimentos balanceados

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Resumen

La molienda es una etapa fundamental en el proceso de elaboración de alimentos balanceados debido a que determina la distribución de tamaño de partícula de los ingredientes, y ésta última influye en la digestibilidad y palatabilidad del producto. El maíz, cuya reducción de tamaño se realiza en una primera etapa de molienda, constituye el principal ingrediente en las formulaciones de nutrición animal, por lo que la capacidad de molienda del mismo es proporcional a la capacidad de producción. Con el fin de aumentar la capacidad de molienda industrial en un proceso de producción de alimento balanceado, se estudia la incorporación de un by-pass de la corriente de maíz molido mediante la incorporación de una zaranda que únicamente dirige el maíz pasante a la etapa de extrusión, evitando una molienda innecesaria. Para ello, se determinó el tamaño de apertura de zaranda que permite mantener la distribución de tamaño especificada al ingreso de la etapa de extrusión. En primera instancia se requirió la adecuación de la etapa de molienda piloto (escala de realización de ensayos) a la escala industrial. Establecidas las condiciones operativas en el molino piloto, se estudiaron 4 tamaños posibles de apertura de zaranda. El tamaño elegido es el que reprodujo la distribución y tamaño medio de partícula del proceso original, logrando aumentar la capacidad en un 16,36 %.

Palabras clave: Molienda, maíz, alimento balanceado, zaranda.

1 Introducción

El proceso de reducción de tamaño de partícula aumenta la superficie por unidad de volumen de los ingredientes, provocando que una mayor porción del interior del grano esté expuesto a enzimas digestivas, permitiendo un mayor acceso a componentes nutricionales como el almidón y las proteínas. [1]
El estudio del aumento en la capacidad de molienda en sistemas de producción de alimentos balanceados, es de gran importancia debido a que los principales ingredientes de las formulaciones requieren en ocasiones, más de una etapa de molienda para alcanzar la calidad requerida.

2 Materiales y métodos

Descripción del proceso industrial

La producción de alimentos balanceados incluye etapas de molienda de la materia prima (granos de maíz, afrechillo, soja, etc.), que son determinantes para las etapas de producción posteriores (mezclado, extrusión). En la Fig. 1.a, se presenta el diagrama del proceso industrial bajo estudio, que consta de una primera etapa de molienda de maíz, cuya harina (A) se envía a un mezclador con el resto de los ingredientes de la formulación (F) para alimentar a una segunda etapa de molienda (C) que genera la distribución de tamaño adecuada (B) para las posteriores etapas del proceso. Con el objetivo de lograr un aumento en la capacidad productiva, se propone la incorporación de una corriente de by-pass (BP) mediante la incorporación de una zaranda, que permita dirigir el maíz que ya posee el tamaño medio y la distribución de partícula (DTP) requerida directamente a la corriente de alimentación de la etapa de extrusión (B') (Fig.1.b).

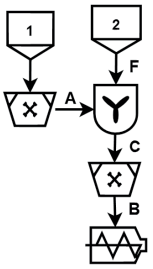

Fig.1.a. Diagrama simplificado del proceso industrial de alimentos balanceados.

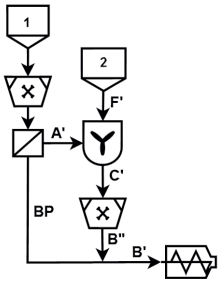

Fig.1.b. Diagrama simplificado del proceso industrial con corriente de by-pass.

Si el caudal de alimentación al segundo molino se mantiene invariante, las corrientes B y B''resultarán iguales. El aumento de caudal será atribuido a la corriente BP. Podrá estimarse mediante la relación BP/B, con la fracción de maíz retenido y de maíz global de la formulación.

Caracterización de muestras

La DTP se caracterizó mediante la utilización de un equipo vibrador de laboratorio (Zonytest, Argentina). Se utilizaron los tamices ASTM: 8 (2,240 mm), 12 (1,600 mm), 16 (1,120 mm), 20 (0,800 mm), 30 (0,560 mm), 40 (0,400 mm), 50 (0,300 mm), 70 (0,212 mm), 100 (0,150 mm), 140 (0,106 mm) y 200 (0,075 mm). Se tamizaron muestras de 100 gramos sometidas a 5 minutos de vibración. Se registró la masa retenida en cada tamiz. El procedimiento se realizó dos veces por mezcla, reportándose los valores promedio.

Determinación de las condiciones operativas en el molino piloto

El equipo de molienda piloto utilizado para la reproducción de las condiciones de molienda del segundo molino industrial fue un molino de martillos Fitzpatrick modelo DAS06 (Waterloo, Canadá) con velocidad de cuchillas variable y cribas intercambiables. Con el fin de proporcionar una alimentación continua y constante al molino, se utilizó un alimentador de tornillo de frecuencia variable. Además, se determinó el tiempo de estabilización para cada caudal mediante el registro de la potencia consumida. Se ensayaron tres caudales de alimentación al molino piloto, operado a 4600 rpm y con una criba de 1 mm de apertura de malla. En cada ensayo, se tomaron muestras del material molido cada 10 segundos, en intervalos de 20 segundos y se registró el consumo de potencia. El caudal elegido, fue el que permitió reproducir la DTP y el tamaño medio geométrico de la corriente B industrial en condiciones estacionarias.

Preparación y determinación de mezclas para molino piloto

La composición de maíz en la corriente B industrial fue de 55, 14 %. Por lo tanto, las corrientes A' y BP deben constituir la misma fracción de maíz en la corriente B'. El caudal de cada una de ellas, es función el tamaño de malla a utilizar en la zaranda. Bajo la misma consideración, se prepararon las mezclas de alimentación al molino piloto.

3 Resultados y discusión

Caracterización de muestras industriales

La corriente de maíz que ingresa al segundo molino (A) posee una proporción de la DTP de la corriente industrial B. Sus diámetros medios geométricos son de 609,0± 2,1 μm y 320,8 ± 2,1 μm respectivamente. Se propone estudiar el efecto del by-pass generado por aperturas de zaranda correspondientes a mallas ASTM 20, 40, 50 ó 70.

Determinación de las condiciones operativas en el molino piloto

Los caudales ensayados en el molino piloto correspondieron a 10 Hz (B1), 30 Hz (B2) y 40 Hz (B3) de operación en el alimentador. La corriente B1 fue la que mejor reprodujo la DTP de B. Su diámetro geométrico resultó de 334,8± 2,1 μm. Por lo tanto, las condiciones operativas del molino piloto quedaron definidas por una frecuencia de alimentación de 10 Hz, una velocidad de cuchillas de 4600 rpm y una criba de 1 mm.

Determinación del tamaño de apertura de zaranda de la corriente by-pass en escala piloto

Se tamizaron muestras de la corriente A, utilizando las mallas ASTM 20, 40, 50 ó 70. Los porcentajes de maíz pasante-retenido que definieron a las corrientes BP y A'

fueron 63,99-36,01%, 37,88-62,12%, 25,16-74.84%, y 11,88-88,12% respectivamente.
Las muestras A' resultantes se mezclaron con muestras de F' respetando la formulación. Posteriormente, se alimentaron al molino piloto. La DTP y el tamaño medio de cada corriente B' obtenidas a escala piloto, se presentan en las Fig.2.a y Fig.2.b, junto a la corriente B1.

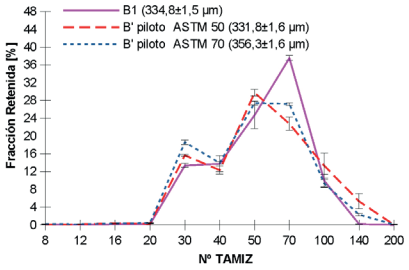

Fig. 2.a. DTP y diámetro medio geométrico de las corrientes B' piloto con tamaños de mallas ASTM 50 y 70 y de la corriente B1.

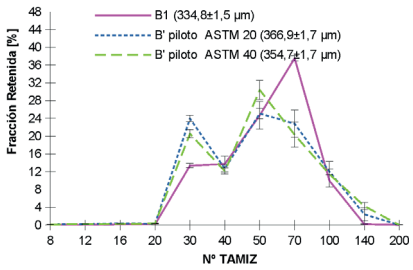

Fig. 2.b. DTP y diámetro medio geométrico de las corrientes B' piloto con tamaños de malla ASTM 20 y 40 y de la corriente B1.

Las mallas que mejor representan la DTP y el tamaño geométrico medio de B1, son las ASTM 40 y 50.

4 Conclusiones

La utilización de una malla ASTM 40 para la implementación de un by-pass en la corriente de maíz molido incrementaría el caudal de producción en 21,31 %, mientras que la utilización de una malla ASTM 50 en 16,36%. Debido a que segunda reproduce la DTP y el tamaño medio geométrico de la corriente B industrial con mayor similitud, se concluye que la mejor opción para la implementación de la zaranda es la malla ASTM 50.

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Programa motivacional en una PyME bahiense

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Breve reseña de la empresa

METROpallets es una recicladora de pallets para la industria. Obtiene los mismos a través de su red de más de mil proveedores distribuidos por el país abasteciendo a la industria alimenticia, agroindustrial y minera con alcance nacional.

Nació como un emprendimiento unipersonal y fue multiplicando su producción desde su creación, en el 2011, llegando hoy día a 12 empleados directos y 10 tercerizados. Con una recuperación anual de más de 300.000 pallets que permite abastecer a más de 100 industrias de la región. Su creación respondía a la necesidad en el mercado de una oferta formal de pallets usados que honre el concepto de la economía circular.

El desarrollo de la actividad permitió conocer a su titular la problemática existente en sector social más vulnerable de la Argentina y la necesidad imperiosa de encontrar soluciones al flagelo del mercado laboral informal. Fue así que la empresa transitó los caminos de la Certificación Internacional como Empresa B desarrollando distintos programas para mitigar la huella de carbono y la desigualdad social, como el programa Despertando Talentos, METROretos, Soy Arbol, Guardianes del Planeta y Hola Abuelos.

Su condición de ser la única Empresa B certificada de la ciudad de Bahía Blanca, le confiere una característica más que especial, donde el triple impacto está en cada decisión de negocio.

Problemática detectada

Por tratarse de una empresa pequeña, de 12 empleados, y donde la pirámide de jerarquías es muy reducida, se detectó un comportamiento que a su vez es propio de la mayoría de las dotaciones de personal de las empresas pequeñas: falta de compromiso a raíz de una ausencia de horizonte de crecimiento dentro de la organización. Esta característica, se origina principalmente por la falta de estímulo y por ende, pérdida de confianza en sí mismos. Se puede concluir que la falta de compromiso atenta, además

de la pérdida de calidad de vida, a la pérdida de productividad dentro de la organización.

Solución implementada

La firma desarrolló un programa denominado Despertando Talentos. El mismo está basado en un Role Play, donde cada colaborador, "juega" a liderar un área distinta de la empresa cada treinta días, conduciendo a todo el equipo de trabajo en lo que a esa área respecta.

Cada colaborador lidera un área. Hoy, son 11 las áreas asignadas:

1. General
2. Herramientas
3. Sustentabilidad
4. Administración Financiera Hogareña
5. Auto elevadores
6. Producción
7. METRO-retos
8. Infraestructura
9. Tecnología
10. Personal o RRHH.
11. Guardianes del Planeta.

Como herramientas, se utilizan reportes gráficos manuales basados en el proceso KAISEN y reportes de frecuencia diaria online, mediante Formularios de GOOGLE. También se apalanca en distintos grupos de interés formados por WhatsApp más el soporte de la app UAALOO. La información generada es procesada y analizada para realizar el feedback correspondiente.

Resultados obtenidos

Se pueden clasificar los beneficios obtenidos en dos grandes áreas: la inherente a la empresa y la inherente a los empleados.

Se podrá ver como algunos beneficios son comunes para ambas áreas, lo que le confiere al programa, características más que interesantes para su implementación.

Para el colaborador, se pueden mencionar, entre los más relevantes, los siguientes beneficios:

- Desarrollo de la capacidad de liderar "sin cargo".
- Desarrollo del poder de "negociación". Sin él no lograría los objetivos que se le plantean.
- Desarrollo del poder de la comunicación efectiva.

- Desarrollo del poder de planificación y organización para evitar los conflictos.
- Desarrollo de la capacidad de "súper" visión.
- Fortalecimiento sobre los conocimientos en sustentabilidad, tecnología y administración financiera hogareña, los cuales son de alcance personal.
- Reconocimiento de las ventajas de liderar en un marco con reglas claras, basadas en el proceso KAISEN.
- Desarrollo en conocimientos técnicos inherentes de la empresa, incluyendo manejo de maquinarias.
- Desarrollo de la confianza en sí mismo. Generando decisiones más asertivas.

Para la organización, se pueden mencionar los siguientes beneficios:

- Atomización y distribución equitativa de responsabilidades.
- Dilución del concepto "irremplazable" de ciertos colaboradores al generar valor y conocimientos en el resto de colaboradores.
- Optimización de los procesos al profesionalizar a cada colaborador.
- Eliminación de conflictos entre colaboradores y empresa por la mejora en la calidad de comunicación y el empoderamiento de cada uno.
- Eliminación del "anonimato" a la hora de encontrar responsables de episodios desafortunados inherentes a la actividad de la organización.
- Reducción drástica del nivel de conflictividad con sindicato a raíz de la mejor calidad de relación con colaboradores.
- Mejora en la productividad del 12%. (últimos 12 meses).
- Reducción de la inasistencia por accidentes laborales en un 90%.

Comentarios finales

El uso del formato del Role Play invita a enfrentar los desafíos sin el clásico temor al fracaso, entonces el escenario se convierte en propicio para que cada colaborador saque lo mejor de sí, incluso sin que ellos mismos sepan que contaban con determinadas aptitudes.

Cada colaborador vive la experiencia con expectativas, ganando día tras día, un logro nuevo. Este ejercicio le permite visualizar con mayor claridad las herramientas que tiene disponible como también las reglas de juego en las cuales debe moverse.

Asimismo el colaborador nota muy rápidamente que se horizontaliza la estructura de la organización, permitiendo que su opinión sea contemplada por todos, a diferencia del pasado, donde su opinión sólo era escuchada por su jefe directo.

Para el empleador, la experiencia también es gratificante. Si bien lleva un gran trabajo en la implementación y control, los resultados en el comportamiento de cada integrante del equipo, permite llevar la empresa a otro nivel de profesionalismo,

descansando responsabilidades de manera más atomizada entre todos, y por ende, mejorar la productividad y la convivencia.

Como conclusión, el proceso implementado arroja beneficios indiscutibles para todas las partes involucradas.

Documentos fotográficos













Sistema logístico integrado para la gestión operativa de carga y despacho de camiones

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Resumen. Este trabajo presenta una visión general de un sistema para poder tomar decisiones de forma eficiente en la gestión diaria del despacho de camiones de polietileno palletizado en el site logístico de PBB Polisur, Bahía Blanca. Su objetivo es utilizar los recursos logísticos y operativos de la manera más competitiva posible, garantizando la entrega de órdenes de clientes en tiempo y en forma. Para ello, se cuenta con recursos limitados: por un lado, existen distintos proveedores logísticos con una disponibilidad variable de camiones para la carga de órdenes. Por otro, los recursos operativos para el despacho de camiones son limitados y es menester usarlos de manera eficiente. Los clientes se encuentran distribuidos en distintos puntos del país y existen fechas de entrega planeadas que deben respetarse a fin de cumplir con las expectativas de los clientes. Los distintos proveedores tienen tarifas distintas para cada destino y conjuntamente existen compromisos en los porcentajes a cumplir para cada ruta y para cada transporte. Para la resolución de este problema complejo, se diseña un sistema que contemple estas restricciones y variables para poder conseguir una solución eficiente.

Palabras clave: logística, Supply Chain, gestión por procesos, secuenciamiento de operaciones, Sistemas ERP, gestión de operaciones, asignación de proveedores.

1 Definición del problema

1.1 Descripción de la operación de despachos

Para poder cumplir con el despacho de camiones, existe un proceso definido en el que actúan varios actores. El proceso comienza con la presentación de un camión en el sector de precarga. Aquí, se realiza un chequeo de las condiciones de la unidad y de la documentación con la que debe contar el chofer para poder seguir con la carga. Si existe algún desvío en este punto, el transporte deberá corregirlo. De lo contrario, la unidad será rechazada.

Luego de haber realizado un chequeo de las condiciones con las que debe cumplir la unidad y el chofer, el sector operativo se comunicará con el sector de precarga para enviar la unidad a cargar.

El sector operativo tiene la carga preparada para comenzar con la carga del camión. Aquí intervienen recursos operativos (auto elevadores, grúas pórtico, reach stackers, inspectores de calidad).

Una vez que el camión finaliza su carga, procede a enlonar si corresponde y es pesado nuevamente. Se le entregan los documentos necesarios (remito, certificaciones de calidad del producto) y finalmente, comienza su tránsito al cliente.

1.2 Definición de condiciones del problema

La descripción anterior permite comprender los pasos que debe seguir cada unidad a despachar para poder comenzar su tránsito al destino asignado. Esta situación requiere del recurso logístico (camión y chofer) y de recursos operativos (personal del sector de precarga y recursos necesarios para la operación del despacho). En ambos casos, ambos recursos son limitados: los camiones con sus choferes pueden no estar disponibles a primera hora para su despacho. Al contrario, su disponibilidad dependerá de la gestión de los recursos del transporte y de la demanda que se le solicite. Además, existen distintos tipos de camión necesarios para cada orden de venta dependiendo del *payload* de la carga.

Por otro lado, los recursos operativos también son finitos. No es posible cargar simultáneamente una cantidad ilimitada de camiones, sino que existe una capacidad limitada para poder llevar adelante esta operación.

1.3 Objetivos e indicadores de la gestión del proceso de despachos

Los principales indicadores a considerar en la gestión de los despachos serán:

1. Concretar el despacho de los camiones en tiempo: para poder llegar a los clientes en la fecha esperada, es necesario cumplir con los tiempos planeados en el despacho.
2. Cumplir con las cuotas pactadas por el sector de compras: cada transporte participó en un proceso de licitación donde se asignaron porcentajes para cada ruta que deben cumplirse lo más fielmente posible. Eso conducirá a tener una estructura de costos logística competitiva.

1.4 Variables de decisión

Dadas estas restricciones que fueron mencionadas en la anterior sección y los objetivos que deben perseguirse de manera continua, tenemos que considerar cuáles son las variables sobre las cuáles es posible actuar y que permiten conseguir mejores resultados en la gestión del proceso.

En primer lugar, la decisión más importante es el proceso de asignación, en donde cada orden de cliente se asigna a un transporte en particular. Esta decisión será fundamental a la hora de conseguir los resultados esperados. En segundo lugar, la determinación de un horario de carga para cada camión será sustancial para poder gestionar los recursos operativos de manera eficiente.

Contemplando tanto las variables como las restricciones, se busca diseñar un proceso que cumpla con los objetivos del dador de carga.

2 Descripción del proceso de gestión

2.1 Actores que intervienen en el proceso

Para comprender el proceso de gestión de los despachos, es importante definir cuáles son las partes que intervienen durante todo el proceso:

1. Mode of Transport Scheduler (MOT Scheduler): se trata de la persona que coordina y es responsable de la totalidad del proceso y pertenece al dador de carga.
2. Carrier: se define así al transporte que será responsable de comunicarse con el MOT Scheduler para disponibilizar las unidades necesarias para el despacho de camiones y de presentarlas en el tiempo convenido para cumplir con los programas operativos.
3. Site Logistics: se trata de la parte responsable de usar los recursos operativos para concretar el despacho de los camiones presentados en el sector de precarga.

2.2 Diagrama del proceso

El siguiente diagrama indica los pasos más importantes del proceso con los responsables correspondientes. En la primera fila, se indica una línea de tiempo referida al día *D*, que indica el día planeado para el despacho.

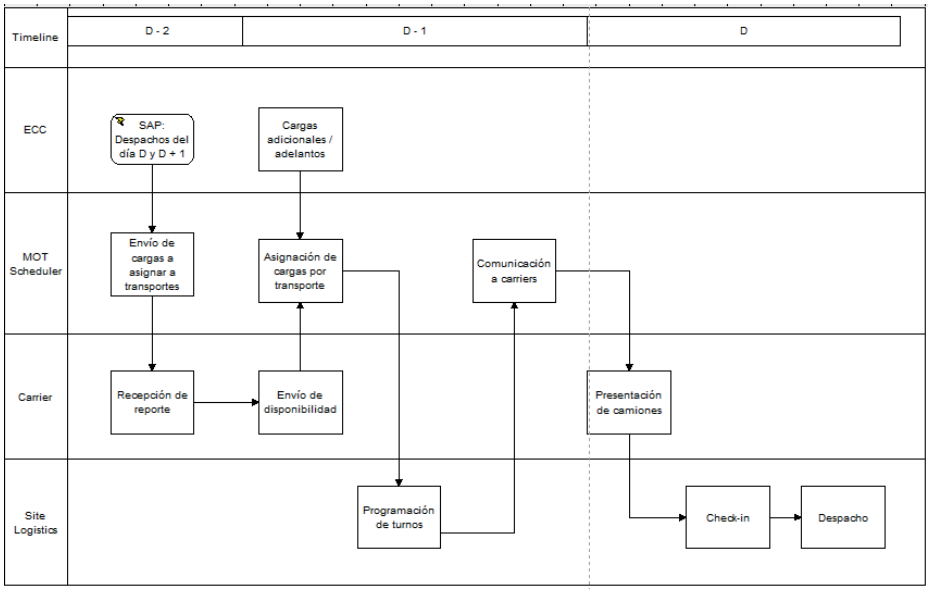

Fig. 1. Diagrama del proceso

El proceso comienza con la información de cargas que deben ser despachadas el día D y D + 1. Esta información indica para cada orden de venta, el destino al que se debe entregar y tipo de camión que se debe utilizar. Esta información es procesada por el MOT Scheduler y proyecta las necesidades a los transportes indicando un horario estimado de carga en un rango definido que depende del tiempo de tránsito que se tenga al cliente y la fecha de entrega planeada.

Cada carrier (transporte), será responsable de recibir esta proyección de cargas con la necesidad estimada en la que deben presentarse las unidades. El día siguiente (*D – 1),* responderá al MOT Scheduler con la disponibilidad que contará el día *D*, indicando en qué rango horario podrán presentarse en pregate, a qué destino pueden asignarse y de qué tipo de camión se trata.

Contando con la información de disponibilidad logística de cada carrier, y agregando órdenes de venta que puedan ser imprevistas, el día *D – 1*, el MOT Scheduler realizará la asignación de órdenes de venta a cada transporte mediante una regla heurística que respete los porcentajes asignados de cada ruta en la licitación previa y que cumpla con el rango horario estimado para poder llegar al cliente a tiempo.

Con esta información, el sector operativo determinará un horario específico en el que se deberá programar el despacho de cada camión, considerando la capacidad operativa instalada y los recursos disponibles. Esta información será recibida por el MOT Scheduler que la retransmitirá a los transportes.

Cada uno de ellos, será responsable de presentar las unidades en el horario pactado para poder cumplir con la programación realizada por Site Logistics. El proceso finaliza con el despacho del camión y su tránsito al cliente.

Innovación en la industria petroquímica

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Resumen

Aplicación de tecnología e innovación con el fin de reducir riesgo, aumentar la eficiencia y reducir costos en los procesos de mantenimiento de la industria petroquímica, específicamente en Ingreso a Espacios Confinados (IEC).

Palabras clave: Innovación, tecnología, Industria.

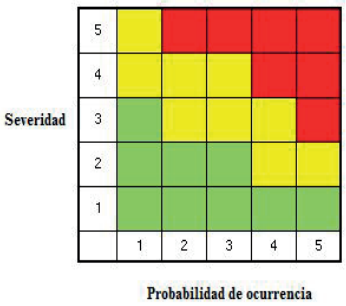
1 Identificación de la oportunidad, Tareas de riesgo

En la labor diaria de la producción química y petroquímica existen gran cantidad de tareas que suponen un peligro para la persona. Desde lo más ínfimo, como ser una caída al caminar, cuyo resultado puede ser una torcedura de tobillo o un raspón en el cuerpo, hasta el peligro que implica trabajar en un espacio confinado dónde una fuga de Nitrógeno provocaría la asfixia de la persona, cuyo resultado final será la muerte.

Aclaramos dos conceptos claves para fundamentar la necesidad de lo expuesto en este trabajo, hablamos de *peligro y riesgo*. El peligro es una condición o característica intrínseca que puede causar lesión, enfermedad o muerte, en cambio el riesgo es la combinación de la probabilidad y la consecuencia de no controlar el peligro en cuestión.

A fines prácticos podemos categorizar las tareas de menos a más riesgosas en función del producto mencionado, siendo "1" la tarea cuyo peligro es menos severo y/o menos probable, y 5 la que tiene mayor consecuencia y/o mayor probabilidad. Como se visualiza en el cuadro siguiente.

Severidad		Probabilidad	
5	Accidente grave, peligro de muerte, gran fuga de tóxicos o combustible a la atmósfera. Impacto a la comunidad	5	extremandamente probable
4	Accidente registrable grave, fuga óxica a la atmósfera. Incidente de proceso.	4	muy probable
3	Accidente registrable, fuga a la atmosfera de combustible o llama	3	probable
2	primeros auxilios, fuga a la atmosfera menor de combustible	2	poco probable
1	accidente precautorio, nada severo.	1	Muy poco probable



Hartas conocidas las consecuencias negativas de un evento de seguridad en la planta, no entraremos en los detalles de por qué es necesario analizar y mitigar los riesgos.

DOW en particular cuenta con miles de empleados, realizando tareas de similares características en todo el mundo y la forma de categorizar las tareas para alertar sobre los potenciales riesgos que conllevan, ha sido a través de los Estándares Críticos para la Vida. Existen dentro de la compañía ocho estándares críticos:

- Ingreso a espacio confinado
- Trabajo eléctrico
- Trabajo en altura
- Trabajo en caliente
- Hidrolavado y lavado a presión
- Aislación de fuente de energía
- Apertura de líneas y equipos
- Permiso de trabajo seguro

Entendemos que al momento de realizar una tarea que encaja en una de las categorías mencionadas se debe tomar recaudos particulares (detallados en cada estándar). Además, éste listado es un excelente punto de partida para definir aquellos aspectos dónde plantear un plan de trabajo con el objetivo de reducir riesgos.

Si bien nuestra organización, y la industria en general, se encuentra en constante mejora de todos los aspectos que hacen a la seguridad y a la implementación de medidas innovadoras, en este trabajo en particular se presentará un caso de éxito aplicado para reducir la tasa de eventos en *ingresos a espacio confinado (IEC)*, disminuyendo la cantidad de horas de exposición.

A grandes rasgos, identificamos como *espacio confinado* a un espacio suficientemente amplio para que una persona ingrese y trabaje, pero,

- Con ingreso y/o salida limitada o dificultosa,
- No diseñado para estar ocupado continuamente,
- Cumple al menos una de las siguientes condiciones,
    - Contiene o tiene potencial de contener una atmósfera peligrosa,
    - Contiene un material que tiene el potencial de envolver a quien esté dentro,
    - Tiene una configuración interna en la cual una persona podría quedar atrapada o asfixiada o,
    - Contiene otro peligro reconocido

Vale aclarar que en toda la industria química, petroquímica y afín vamos a encontrar gran cantidad de equipos, como ser calderas, pulmones, piletas, intercambiadores, hornos, etc., que, por cuestiones de seguridad de proceso, mantenimiento, inspección y regulaciones, requieren que se realicen tareas en su interior.

Existen al menos dos tipos de medidas a considerar para reducir riesgos:

1.1 Colocación de barrera física o uso de elemento de protección personal.

Instalar barreras que impidan el contacto entre la persona y la fuente de un riesgo. El peligro sigue estando, se disminuye o anula, la probabilidad de que tenga lugar el accidente o las consecuencias de este. El condicionante ante este tipo de medidas es que una mala implementación podría derivar en un evento, ya que la fuente del peligro sigue estando.

Ejemplo aplicado: Colocación de placas.

Previo ingreso a un espacio confinado, se colocan placas en las cañerías que conectan al equipo en cuestión con el resto del proceso, con el objetivo de asegurar que ningún fluido no deseado (como ser N2, Etano, Etileno, o cualquier producto nocivo) pueda ingresar mientras una persona se encuentra dentro trabajando.

Una placa mal colocada, o una válvula mal cerrada y/o con fuga, puede derivar en un evento de seguridad.

Ejemplo aplicado: Uso de equipo autónomo de respiración.

Implica agregar un grado de complejidad para realizar la tarea, mayores tiempos, costos y mayor exposición al peligro con menor riesgo.

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1.2 Eliminar la tarea o modificar la forma de realizarla.

Modificar la naturaleza del sistema y/o el procedimiento de ejecución de tal forma que la tarea en cuestión deje de ser necesaria o se ejecute de otra manera y por lo tanto el peligro deje de existir.

Ejemplo aplicado: Uso de equipo autónomo de respiración.

Durante los últimos años en el complejo de Bahia Blanca se comenzaron a utilizar robots comandados a distancia para realizar cierto tipo de inspecciones, de esta manera se evita el ingreso a espacio al espacio confinado.

2 Plan de acción

Como ya se mencionó, el objetivo es reducir al mínimo e indispensable las horas hombre de IEC. Por lo tanto, se hizo necesario avanzar con medidas de tipo 1.1.2, es decir no agregar una barrera de protección, sino que modificar la forma de realizar la tarea o la tarea en sí misma. Para lo cual presentamos y llevamos adelante dos proyectos.

2.1 Uso de robots para realizar inspecciones

Se han utilizado desde 2018 y los resultados han sido positivos. Gran cantidad de inspecciones dónde implicaba que una persona debía ingresar a un equipo, se han reemplazado por el ingreso de un robot.

Principalmente utilizando tres modelos, en primer lugar “el Crawler” robot simil carro, con capacidad de imantarse (a superficies ferromagnéticas) y moverse dentro del equipo, incluso de manera vertical (como se observa en las fotos 1 y 2) posee cámaras de alta definición y se puede inspeccionar en vivo (ver foto 3). El único condicionamiento es que las paredes del equipo deben estar con cierto grado de limpieza para que pueda imantarse y, por supuesto, requiere a alimentación eléctrica.

Foto 1



Foto 2



Foto 3



En segunda instancia contamos con la cámara “spectrum” que es básicamente una cámara de alta definición con alcance 360° (manejable a distancia) y la capacidad de ingresar al equipo a través de una extensión manual.



En tercer y último puesto, el uso de drones para inspección. Cubiertos con una jaula de fibra de carbono, incluye linterna led y capacidad de filmar en HD, cámara termográfica, además de poder ver en vivo a través de computadora.



2.2 Uso de cámaras vigía para evitar persona extra dentro de EC.

Según estándares de DOW, siempre que una persona esté dentro de un espacio confinado debe ser monitoreada; hasta la implementación del uso de cámaras, esto se hacía a través de un observador, o una cadena de ellos en caso de ser necesario, estando el último observador fuera del espacio confinado.

En la actualidad se cuenta con dos cámaras conectadas por cable a un monitor. De esta forma el vigía externo observa a las personas ubicada en el interior, a través de un monitor. Las cámaras cuentan con una base magnética que les permite adosarlas a cualquier superficie ferromagnética.







El sistema de Video está formado por 2 cámaras Hikvision IP con resolución Full HD, vinculadas a un NVR Móvil Hikvision, con un monitor led de 12".

El sistema NVR Móvil se encuentra asimismo instalado en una maleta estanca con ruedas, construida en plástico de alto impacto, donde a su vez se encuentra el monitor led de 12". El sistema se alimenta con una batería de Gel de 12v-17Ah, la cual provee una autonomía aproximada de 6 hrs. Sobre el exterior de la maleta se encuentran los jack industriales de RJ45 uno para cada cámara y un conector para el cargador de la Batería.

Medidas del gabinete: medidas externas 56 cm x 35cm x 23cm, medidas internas 50cm x 28cm x 19cm.





Las cámaras Ip mini Domo se instalaron sobre una caja estanco de 10 x 10 cm, cuya base posee un imán de 8 cm de diámetro por 3 de espesor, con capacidad de soportar 1,5 Kg de fuerza. En el exterior de la caja se colocó un Jack industrial Rj45, desde donde se conecta el cableado hasta la NVR.

Como medida de seguridad adicional las cajas de las cámaras poseen un cable de acero con ganchos de apertura rápida, para asegurar la cámara a la estructura. Esto es pensando en el momento de la instalación del cableado, se realice una fuerza mayor a la soportada por el imán y la cámara no caiga al piso quedando colgada de la estructura.







Para conectar las cámaras al gabinete se cuenta con 4 cables UTP exterior doble vaina de 30 metros de largo con fichas RJ45 industriales en cada extremo (hembra y macho), esto permite extenderlo de ser necesario. Se incluye un cargador de batería externo, con indicadores de estado de la batería y la opción de carga rápida.

Un punto de relevancia consiste en que a pesar de que existe en el mercado internacional este tipo de equipamiento, optamos por el diseño, configuración, armado y provisión en conjunto con un proveedor local, logrando un producto apto para el fin que fue pensado, a un valor substancialmente menor al del equipo importado (un 20% con respecto al valor del importado)

3 Resultados

Consideramos que los resultados fueron óptimos, porque se cumplió, y sigue cumpliendo cada vez que se utiliza un equipo de los mencionados, el objetivo principal que es evitar horas hombre dentro de espacio confinado.

Además, vale mencionar que de manera indirecta la organización se benefició de otra forma, más imperceptible que la primera, pero en el mismo escalafón de importancia: crecimos en creatividad, en capacidad de innovar, de asumir el riesgo que implica utilizar nuevas herramientas, en salir de la zona de confort, analizar nuevas ideas/formas/métodos, lo cual involucra que quienes fueron y son parte de este proceso cambiaron y cambiarán para siempre su manera de razonar ante futuros desafíos, articulando además con proveedores de servicio y tecnología locales, potenciando el desarrollo en conjunto. Esto, junto a otros valores, es lo que ayuda a las organizaciones como la nuestra a crecer, a mejorar, a adaptarse, a producir más eficientemente y con mayor seguridad.

Referencias

El trabajo fue preparado en su totalidad con material de DOW Argentina, de carácter confidencial. En caso de necesitar referencias internas específicas se puede consultar al autor, quien a su vez ha utilizado:

1. LCS, Life Critical Standards (DOW / Intranet)
2. Circular mensual Innovación (DOW/ Correspondencia interna)
3. Presupuesto Vigilan “Propuesta Sistema de Video Móvil para Vigía Electrónico”.
4. Reporte TA Planta Solución (EPE) – Integridad mecánica / uso robots.

Indice de Calidad de Vida Laboral

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Breve reseña de la empresa

Husal Construcciones y Servicios, es una empresa radicada en Ingeniero White, Bahía Blanca; dedicada a prestar servicios de reparación y limpieza de recipientes sometidos a presión y tanques, fabricación de cañerías y estructuras metálicas, armado y desarme de andamios, servicio de hidro-grúa, construcción de obras civiles, servicio de limpieza de edificios, oficinas y mantenimiento de espacios verdes, servicio de hidro-lavado de alta presión, hidro corte e hidro demolición.

La empresa comenzó sus actividades en la Argentina en 1982, como una empresa de construcciones y servicios. La creciente demanda de servicios complementarios para dichos proyectos llevó a la empresa a ampliar sus actividades, diversificándolas en toda la Argentina.

La Misión de Husal Construcciones y Servicios S.A. es: "Desarrollar, construir y brindar servicios al entorno empresarial e industrial".

La Visión de Husal Construcciones y Servicios S.A. es: "Ser líder: la primera opción del Cliente, en servicios de construcción y desarrollo de proyectos empresariales e industriales".

Desde sus inicios Husal ha sido una empresa comprometida activamente con la mejora continua del ámbito comunitario, el crecimiento sustentable y el cuidado medioambiental. A partir de estas premisas organizacionales, se comienza a trabajar sobre el concepto de RSE.

Para llevar adelante estos principios, la Dirección participa en forma activa, con el fin de fortalecer la integración humana y profesional de toda la Organización, como base para el mantenimiento y la mejora continua del Sistema de Gestión Calidad, Medio Ambiente, Seguridad y Salud en el Trabajo, así como también proveer los recursos necesarios para asegurar que todo el personal propio y contratado puedan cumplir con los principios de la presente política.

Problemática detectada

Con base en la productividad que venía manteniendo la empresa hasta el año 2015, la misma se vio en la necesidad de medir de forma cuantitativa, a través de un Índice, cuán motivados estaban sus empleados. De esta manera consideraban que, aplicando acciones incentivadoras y motivadoras, permitirían que el trabajador aumentara su productividad o mejorara su trabajo.

El índice que construyeron, llevó el nombre de Índice de Calidad Vida Laboral (ICVL), y constaba de una serie de preguntas organizadas de modo tal que se obtuvieran resultados específicos para los siguientes 6 ejes:

- Caracterización demográfica del personal
- Distribución del personal, según actividad realizada en la empresa
- Situación personal con el trabajo
- Características laborales
- La empresa
- Vida personal

Solución implementada:

Una vez realizada la primera parte del índice, la Dirección de la empresa junto a los asesores externos, se reunieron para definir las acciones motivadoras que generarían el aumento de productividad en el empleado, teniendo bien en claro que las mismas no serían del tipo incentivo monetario, ya que lo que se buscaba era generar en el trabajador de Husal, un compromiso y sentido de pertenencia para con la empresa que traspasara las implicancias económicas.

Dentro de las acciones que se diseñaron, se destacaron en su puesta en marcha las siguientes:

- El proyecto “Mi Casa”: se brindaron materiales de construcción y mano de obra voluntaria para aquellos empleados que tenían falencias en sus viviendas o que las mismas repercutían de forma negativa en su calidad de vida.
- Torneos de futbol: se organizaron torneos de futbol para los empleados interesados buscando que los mismos trabajaran en equipo para un fin común externo del ámbito laboral, pero que sentaría una base para futuras actividades.
- Capacitaciones, coaching en resolución de conflictos: cuando se realizó la primera etapa del relevamiento, la empresa notó que una importante cantidad de empleados se veían interesados en que la Organización le brindara las herramientas para resolución de conflictos dentro del ámbito laboral, para

ello se les otorgó la posibilidad de formar parte de capacitaciones que abarcaran los diferentes ámbitos de interés en ese sentido.

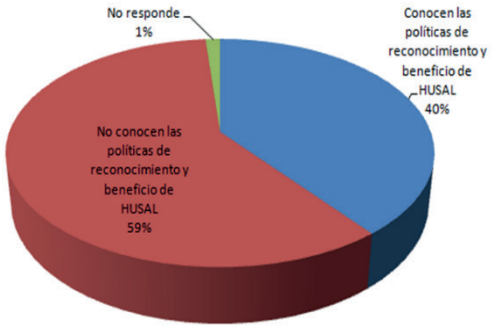
Resultados obtenidos

Una vez llevado a cabo las "acciones motivadoras", se volvió a realizar una etapa de medición del Índice con la premisa de buscar resultados o diferencias comparativas respecto a la primera medición.

Los resultados y análisis realizados llegaron a la conclusión de que las acciones aplicadas, si bien aportaron un grado de incentivo e interés en el empleado que participó de ellas, no se produjo el "efecto contagio" que se esperaba para el resto de los trabajadores. Es decir, la medición del índice continuó en valores similares a los obtenidos en la primera etapa.

Representación grafica de algunos de los aspectos más relevantes encuestados.

Más de la mitad de los empleados (**59%) manifiestan no conocer las políticas de reconocimiento y beneficio de HUSAL.**



Quienes las conocen (30 respuestas), lo hicieron de diferentes maneras:

- *"Las conocí mediante charlas o avisos y folletos informativos realizados por Husal."*

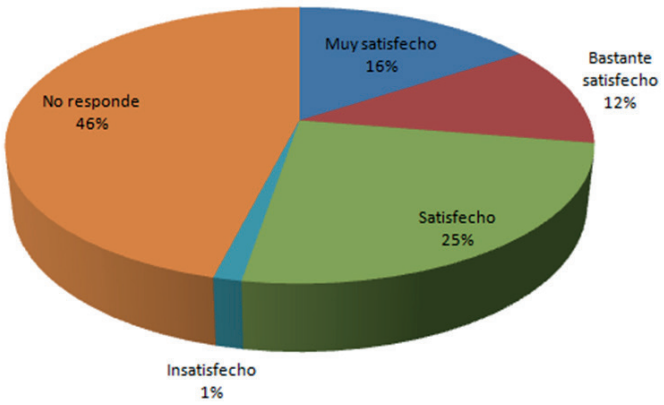
- *"A través del encargado/supervisor o técnicos".*

- *"Porque en el obrador hay un cartel con las políticas".*

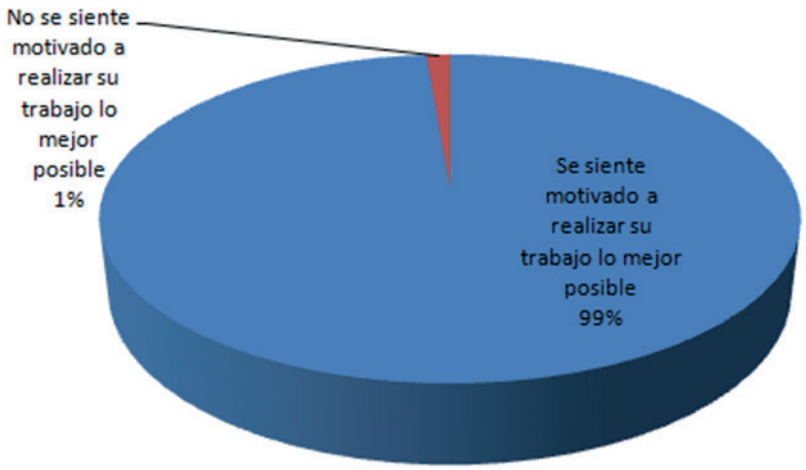
- *"Por el puesto que ocupo, tengo mucho contacto con los puestos gerenciales y ellos transmiten su filosofía".*

- *"Por experiencia propia y también al verlo plasmado a determinados empleados".*

Entre quienes fueron reconocidos o beneficiados, es alto (53%) tienen un alto nivel de satisfacción con lo que han recibido.



Prácticamente el total de los empleados se siente motivado a realizar su trabajo lo mejor posible.



Comentarios finales

Independientemente de los resultados obtenidos a través de la medición del ICVL, la empresa tiene, dentro de sus objetivos principales, los siguientes:

- "Optimizar el clima laboral brindando herramientas y capacitación para la toma de decisiones, la comunicación efectiva, la resolución de conflictos y el trabajo en equipo. Fortalecer la pertenencia y la capacidad de evaluar los procesos laborales. Brindar espacios para el esparcimiento y la mejora de la calidad de vida".
- "Fomentar la participación en el Voluntariado Corporativo Motivar a todo el personal propio y contratado, así como clientes y proveedores a comprometerse en acciones de RSE que desarrolla la empresa. Fortalecer el compromiso con el cambio social y el cuidado medioambiental".

De esta manera queda clara la postura de Husal Construcciones y Servicios S.A. para con sus empleados y la calidad de entorno laboral a la que aspiran.

Adaptaciones a las nuevas demandas y tendencias

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Breve reseña de la empresa

Sueño Austral es una joven empresa que desde sus inicios, en 1997, representa a Piero SAIC en la provincia de La Pampa, sur de la provincia de Buenos Aires y en todo el sur Argentino. En un primer momento, alquilando un galpón de 250 metros cuadradosse presentó a Piero un proyecto para realizar la representación de su marca en tres etapas bien marcadas, que tenían que ver con el territorio. En primer lugar, todo el Valle hasta Esquel, en segundo lugar, el sur hasta Comodoro Rivadavia y en tercer lugar el sur hasta Ushuaia.

Se comenzó, como toda empresa familiar, haciendo todas las tareas (viajes, administración, depósito, reparto, etc.) y con el correr de los años no sólo creció como empresa, sino logró ser reconocida como referentes en el mercado. Hoy cuenta con un depósito de 3.000 metros cuadrados, 500 metros cuadrados de oficinas y showroom, 4000 de fábrica, y un staff de más de 40 colaboradores. La firma nunca perdió de vista que es una empresa de servicios, que masallá de la venta de mercadería se debe al cliente. Su evolución indica que marcha por el buen camino.

Con el avance del tiempo los directivos se dieron cuenta que existía un potencial en toda la zona para poder empezar a fabricar productos relacionados con el rubro en el que estaban trabajando, y además empezar a ser protagonistas principales en la historia de nuestra empresa. Es por esto que se decidió ampliar el campo de negocios y fabricar juegos de living, guata, vellón, sábanas, acolchados, almohadas, matelaseados, etc., lo que hizo que se pudiera tener una mayor participación dentro de los clientes y en el mercado en general.

Problemática detectada

Con el correr de los años los directivos se dieron cuenta que era fundamental para la evolución de la empresa familiar dar un salto de calidad y mejorar en los distintos tipos de problemas que lógicamente fueron apareciendo juntos con el crecimiento. La distancia entre los clientes y el elevado valor de los fletes al sur hacen que el despacho de la mercadería sea difícil y costoso. Teniendo en cuenta que la mayoría de

los transportes están en Buenos Aires, enviar la mercadería de Bahía Blanca es un poco más complicado.

Desde que empezaron a despachar los juegos de living, se dieron cuenta que el embalaje tenía que ser muy bueno y que el transporte no tenía que hacer trasbordo. Por ejemplo, en un camión entran 35 juegos de living y la distancia a Ushuaia desde Bahía Blanca es de 2450 km., es decir es muy alta la incidencia del costo de transporte. Por lo expuesto, se decidió empezar a cambiar e innovar para que poco a poco mejoren los resultados.

Solución implementada

El primer cambio fundamental en la empresa fue la compra de un camión propio para mejorar la entrega. En poco tiempo se amplió la flota y hoy cuentan con tres camiones para el reparto de su propia mercadería. Además, tercerizaron los viajes desde Buenos Aires a Bahía Blanca pero el reparto interno quedó en manos de la empresa. Rápidamente tuvieron un crecimiento en las ventas dado que la incidencia del flete fue mucho menor, y al completar el camión con varios clientes la entrega se hizo con mayor frecuencia. Esto también mejoró la participación de Sueño Austral en los clientes dado que dejaron algunas marcas para inclinarse en esta.

La innovación más significativa fue la de diseñar un juego de livingtotalmente desarmable, que entre en cajas, sea fácil de armar conteniendo sus propias herramientas, que tenga la opción de puerto USB para carga de celulares y tablet, que se pueda cargar en un camión con autoelevador y se pueda estibar en estanterías.Después de varios meses de trabajo se logró un producto de buen precio, que se ajusta a la calidad pretendida, fácil de armar y estandarizado en su producción. Esto mejoró mucho el costo de flete dado que se pudo duplicar la cantidad de juegos de living trasladados.

Se confeccionó un tutorial en video para el armado, que reemplaza al típico manual de instrucciones, y se grabó un spot publicitario en uno de sus principales clientes, la Cooperativa Obrera, para dar sentido práctico a todo lo que pregona el producto. Además, se registró la marca LIVING-BOX - TU LIVING EN CAJA.

Finalmente, la empresa tiene como proyecto concretar la compra de una máquina para fabricar el modelo de almohadas más vendido, con lo cual podría duplicar la fabricación y sobre todo dejar libre la máquinade cardado para continuar creciendo en la venta de guata, vellón, y en la fabricación de acolchados y matelaseados. Debido a la situación actual es un proyecto que quedará para más adelante.

Resultados obtenidos

La empresa considera muy favorables los resultados de las mejoras implementadas, particularmente en relación al nuevo juego de living desarmable. Los mismos se detallan a continuación:

- Con la compra de camiones propios aumentaron las ventas y mejoró la calidad en las entregas bajando considerablemente el costo de flete a los clientes.
- En un camión se pueden cargar el doble de productos, por lo que bajó considerablemente el costo de flete. Para un cliente de Río Gallegos, por ejemplo, el flete disminuyó por lo menos al 50%.
- Se pueden apilar los juegos de living en estanterías de a 10 cajas sin dañar la espuma.
- El armado es sumamente fácil, a tal punto que una pareja sin experiencia lo puede hacer en menos de 30 minutos.
- En los edificios de departamentos, donde los juegos de living, en especial los esquineros, no pueden entrar o subir por escaleras, los mismos pueden ser subidos por ascensor o escalera gracias a su embalaje en cajas.
- El puerto USB que da la posibilidad de cargar dispositivos mientras se descansa o se mira TV generó un impacto muy importante en el posicionamiento del producto.

Comentarios finales

La empresase encuentra sumamente conforme con las mejoras implementadas, particularmente con la innovación realizada en el juego de living desarmable. Pese a que no se pudo realizar un lanzamiento del producto como lo tenían planificado, se logró posicionar el producto y los comentarios de los clientes son positivos. Se prevé realizar el lanzamiento cuando se retorne a una situación más normal, para no perder trascendencia.La idea de la empresa es seguir creciendo y expandiéndose en la región con locales.Buscan agrandar la fábrica y llegar a tener 20 locales entre propios y franquiciados.

La incertidumbre y las duras condiciones productivas dificultan la marcha de los proyectos pero no los detienen. En este sentido, la firma siempre fue optimista y apostó a ser protagonista de su propio desarrollo.

Documentos fotográficos








SUEÑO AUSTRAL S.A.
Industria Argentina


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Herramienta de Gestión – Pool de Contenedores Vacíos para ordenes MPC

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Resumen.
El presente escrito tiene como objetivo describir la herramienta de gestión utilizada para definir las acciones a realizar con respecto a la gestión del pool de contenedores vacíos, que luego se utilizarán para ordenes de exportación marítimas.
Estos contenedores poseen cierta cantidad de días "libres" (en general, 21 días), que una vez superados, comienzan a generar costos diarios de "Demurrage/Dentention", los cuales son abonados una vez que los contenedores ingresan nuevamente a una terminal portuaria. Por eso, es fundamental contar con un pool de vacíos adecuado, que permita cumplir con la demanda, aunque sin sobredimensionarlo, ya que si no son utilizados en el futuro próximo, se traducirán en extra costos.
Esta herramienta de gestión (la cual está basada en un solver de modelo lineal), propone una serie de acciones a tomar para disponer del número apropiado de contenedores vacíos. En función de la disponibilidad de contenedores y de la demanda confirmada y proyectada de las próximas semanas, la herramienta selecciona las acciones más eficientes para incrementar o disminuir el pool según corresponda.

Palabras clave: Supply Chain, Logística, MPC, Vacios, Navieras, Detention, Eficiencia.

1 Gestión del pool de vacíos

1.1 Operación Histórica y Oportunidad de Mejora

La operación de despacho de ordenes de exportación marítima cuenta con numerosas particularidades, una de ellas consiste en la necesidad de contar con el producto consolidado en un contenedor determinado, que luego será trasladado hasta una terminal portuaria y embarcado hasta destino. Por eso, es que Dow cuenta con cierto inventario de contenedores vacíos de distintas navieras, que luego utilizará para estas órdenes.

Históricamente, el pool de vacíos se va rotando a medida que los contenedores llenos ingresan a la terminal. La gran mayoría de los traslados se realizan en tren, por lo que

el mismo vagón que se utiliza para enviar el contenedor consolidado con producto, luego se utiliza para retornar el vacío desde la terminal.

Sin embargo, el dimensionamiento del pool de vacíos no se trata de algo trivial, si no que requiere de análisis. Sobredimensionar el numero de contenedores a la espera de producto para embarcar no resulta eficiente en términos económicos ni operativos (falta de espacio), mientras que subdimensionarlo implica dejar de cumplir con la demanda.

Centrándonos en los términos económicos, es importante resaltar que las navieras conceden cierta cantidad de días "libres" a los contenedores que entregan a sus clientes. Una vez que ese tiempo finalizó, se empiezan a generar costos diarios de "Detention", que luego serán abonados cuando el contenedor retorne a alguna terminal portuaria.

Por eso, nos pareció oportuno diseñar una herramienta que permita gestionar de manera integral la disponibilidad de vacíos en la planta de Bahía Blanca. De esta manera, acercarnos al punto optimo con respecto al pool, y disminuir el tiempo humano dedicado a la toma de decisiones respecto a este tópico.

1.2 Herramienta de Gestión de Vacíos

La herramienta de gestión (desarrollada bajo el modelo de Solver Líneal) incluye información con respecto al pool actual de cada una de las navieras, demanda confirmada y proyectada en el tiempo de cada una de ellas, cantidad de contenedores en tránsito retornando a la planta y la programación de envíos de los contenedores a cada una de las terminales. Así, tenemos un estado inicial, en el cual, a partir del Stock Actual, se suman los ingresos programados de vacíos y se resta la necesidad confirmada y proyectada de los mismos. Aquí, es probable que el pool de vacíos no sea suficiente o sea mayor al necesario, por lo que se deben tomar acciones para alcanzar el estado deseado.

El objetivo de la herramienta es claro, disponer de un pool de vacíos suficiente para cumplir con la demanda, pero de manera óptima. Por eso, es que se define un "Stock Objetivo" semanal de vacíos, que se define como la necesidad de la semana próxima, más la mitad de la demanda proyectada para la semana posterior. Así mismo, para evitar el sobredimensionamiento del pool, se define una restricción que limita la tolerancia de disponibilidad de vacíos sobre el estado óptimo.

Por otro lado, las acciones necesarias para llegar a este Stock Objetivo son muy variadas (dependen de cada naviera, de la terminal utilizada por la misma, por la necesidad en el tiempo de los contenedores, etc.) y como es de esperarse, tienen diferentes costos asociados. A los efectos de la herramienta, se definieron costos cualitativos para cada una de las posibles acciones, de manera de jerarquizar las opciones que nos permitirán cumplir con nuestro objetivo. Así, la herramienta busca minimizar la función objetivo (sumatoria de acciones por el costo de cada una de ellas) reflejando las prioridades operativas. Luego, existen diversas restricciones que se definen en función de la operación particular de cada destino, naviera y terminal portuaria, que obviamente limitan la resolución de cada estadío.

Cabe resaltar que las acciones propuestas para cada naviera, puede tener consecuencias sobre el pool de otra. Por eso, es fundamental definir las variables de decisión de manera simultanea para alcanzar la solución óptima.

Finalmente, la herramienta provee una serie de acciones que definen el plan de acción semanal con respecto a la gestión del pool de vacíos. Estas actividades son informadas a cada uno de los eslabones de la cadena y sus respectivos responsables en una reunión semanal.

1.3 Actores Intervinientes

En el proceso de gestión del pool de vacíos hay diversos actores involucrados, a saber:

- Analista Logístico: Responsable de gestionar el proceso y consolidar la información de los distintos eslabones, es quien define el plan de acción semanal con respecto al pool de vacíos de cada naviera.
- Operador Logístico Bahia Blanca: Responsable del consolidado y despacho de contenedores a exportar, además coordina acciones en función del plan definido.
- Operador Logístico Bs As: Responsable de la gestión de retorno de contenedores (o no) desde terminales en GBA, en función de las acciones definidas en el plan semanal.
- Freight Forwarder: Encargado de gestionar los bookings para las ordenes MPC y ordenes de retiro de vacíos de cada una de las terminales.

1.4 Implementación

Dado el panorama mundial de incertidumbre, de manera conservadora DOW había decidido incrementar fuertemente el pool de vacíos en Bahia Blanca, de manera de asegurarse la posibilidad de abastecer su demanda, aunque asumiendo el riesgo de un incremento importante de los costos de Detention.

Así, la herramienta de gestión se comienza a implementar a fin de Mayo de este año, con el claro objetivo de gestionar el pool de vacíos de una manera más eficiente. Además, se coordinan reuniones semanales de seguimiento y definición de plan de acción, en la que participan todos los eslabones de la cadena de suministro.

Los resultados de la gestión integral de vacíos se reflejaron rápidamente en la disminución de los costos de Detention abonados. A partir de la implementación de las estrategias mencionadas, los extracostos afrontados en términos de Detention disminuyeron a un tercio, con respecto al promedio de los primeros cinco meses del año (ver Fig. 1).

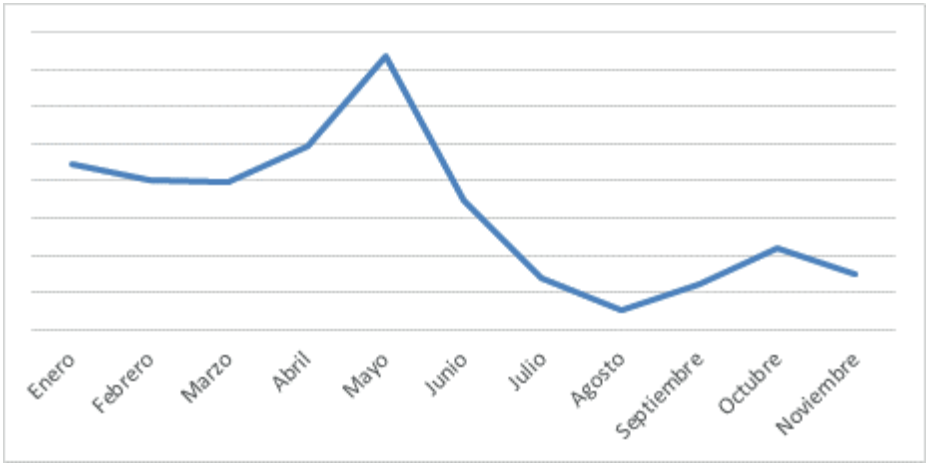

Fig 1. Distribución de costos por Detention en 2020.

Desarrollo de un Caso de Uso de Industria 4.0 en una Planta de Producción de Aguas y Gaseosas

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Resumen

Existen numerosos trabajos que describen y recopilan las tecnologías utilizadas en el contexto de la Industria 4.0 y sus beneficios. Sin embargo, los trabajos que exponen casos de uso concretos son más escasos. El objetivo del trabajo es presentar los resultados preliminares del desarrollo de un caso de uso de Industria 4.0. La metodología se basa en el modelo de cinco etapas. Asimismo, la metodología incluye entrevistas a expertos de la planta y encargados de Planeamiento, la observación directa, y el análisis de documentos de la planta. Se considera una planta de producción de aguas y gaseosas. Se describe el relevamiento preliminar de los procesos productivos de la compañía, donde se podrá apreciar brevemente el análisis de las líneas productivas de la compañía, las partes integrantes, requerimientos productivos, áreas intervinientes y principalmente permitirá la detección de problemas actuales, potenciales y futuros. Además, se incluye la evaluación de madurez sobre la aplicación de tecnologías de la Industria 4.0 en el área de Producción. Finalmente, a partir de los resultados preliminares se plantea el trabajo futuro en el desarrollo del caso de uso.

Palabras clave: Industria 4.0, Modelo de Madurez Industria 4.0, Producción.

1 Introducción

La Industria 4.0 implica una transformación a partir nuevas tecnologías industriales, tales como robots avanzados, manufactura aditiva, realidad aumentada, big data, computación en las nubes, entre otras [1], [2], [3]. La revolución en la industria trae consigo impactos significativos en la producción, así como un incremento en la eficiencia de la utilización de recursos, y mayor capacidad para integrar y aumentar la flexibilidad en las líneas de producción. La penetración de las tecnologías de Internet en la Industria 4.0 puede ir más allá de los procesos de fabricación incluyendo el desempeño logístico dentro de una Red Global de Producción. Una Red Global de Producción se refiere a un conjunto de entidades de producción distribuidas (globalmente) que contribuyen a la creación de valor.

Con referencia a la República Argentina, la consultora The Boston Consulting Group [4] elaboró un informe basado en un relevamiento entre 78 ejecutivos de 66

grandes empresas industriales de diferentes sectores. Se indica que si bien los ejecutivos conocen las tecnologías pocas empresas invirtieron en ellas. Solo el 30% indica que en su empresa implementaron una iniciativa concreta. El mayor grado de implementación se observa en las tecnologías relacionadas con la seguridad e infraestructura de datos. Sin embargo, solo el 9% indica que actualmente ha implementado tecnologías de fábricas inteligentes, control de la producción y diseño de fábrica digital. Las principales barreras para su adopción son la falta de personal calificado (70% de las respuestas), la incertidumbre respecto al retorno económico de las inversiones (65%), y la resistencia al cambio y la innovación (64%).

Si bien existen numerosos trabajos que describen y recopilan las tecnologías utilizadas en el contexto de la Industria 4.0 y los beneficios [5], [6], los trabajos que exponen casos de uso concretos son más escasos. Este trabajo tiene como objetivo desarrollar un caso de uso de Industria 4.0 para un área organizacional que mejore la calidad de los productos y el desempeño logístico. Se trata de un proyecto en desarrollo y en este trabajo se exponen los resultados preliminares.

El trabajo está organizado de la siguiente forma. A continuación, se describe la metodología. En la sección 3 se resume el marco de trabajo utilizado. En la sección 4 se presentan los avances y en la sección 5 se incluyen las conclusiones preliminares y el trabajo futuro.

2 Metodología

El objetivo del trabajo es desarrollar un caso de uso de Industria 4.0 para un área organizacional que mejore la calidad de los productos y el desempeño logístico. Se trata de una planta de producción de aguas y gaseosas. Por su tamaño, se considera grande, o gran empresa, de acuerdo a la clasificación de empresas en Argentina, según la Secretaría de Empleo [7] en la cual se indica que si la organización cuenta con más de 200 empleados permanentes, le corresponde la categoría más alta. Para la Unión Europea [8], en base a al tamaño y complejidad de la empresa, esta se clasifica como mediana dado que la valuación de sus activos no la ubicarían en el escalón más alto. A efectos de desarrollar el caso de uso en la industria 4.0, se siguen las etapas de trabajo propuestas por Peukert et al. [9] para pequeñas y medianas empresas. En este caso la unidad de análisis será la planta. La metodología se basa fundamentalmente en las entrevistas a expertos de la planta (Gerente de producción, Jefe de producción, Jefe de mantenimiento, supervisores de producción y encargados de Planeamiento/Cadena de Suministros), la observación directa, y el análisis de documentos de la empresa tales como manuales de procedimientos.

3 Marco referencial teórico

Peukert et al. [9] observan que las empresas pequeñas y medianas, muchas de las cuales operan como proveedores en redes de producción globales, muchas veces están más atrasadas en la implementación de la Industria 4.0. Los autores proponen un modelo de procesos de cinco etapas que busca hacer uso del potencial de la Industria 4.0 en términos de mayor calidad del producto e indicadores de desempeño logístico

dentro de la red. La propuesta identifica problemas potenciales que impiden una mejor calidad del producto o desempeño logístico, y a partir de esos problemas, se derivan soluciones que aprovechas tecnologías de la Industria 4.0. La propuesta de Peukert et al. [9] se basa en los modelos de procesos de Noehring et al. [10] y Bildstein y Seidelman [11] y extiende el trabajo para aplicarlos en empresas pequeñas y medianas operando en redes de producción global. A continuación, se resumen las cinco etapas propuestas en el trabajo de Peukert et al. [9].

Etapa inicial. El objetivo es identificar problemas potenciales que impiden un incremento en la calidad de los productos y el desempeño logístico. Para el problema identificado y seleccionado se desea desarrollar una solución basada en tecnologías de la Industria 4.0.

Análisis. Para el problema identificado se debe registrar el estado de las cosas para elaborar capacidades clave y debilidades y desarrollar abordajes preliminares de solución. Previo al análisis de los procesos afectados por la red de producción global, se realiza un estudio de las competencias de la compañía con respecto a la Industria 4.0. El estudio se basa en utilizar una herramienta denominada Modelo de Madurez Industria 4.0 para considerar el producto y los procesos de producción. Para los productos, se desea entender en qué medida se puede agregar valor a los productos en base a tecnologías de Industria 4.0. Además, se desea entender el estado actual de los procesos de producción y vislumbrar cómo se podrían optimizar o cómo se podrían reducir los costos utilizando Industria 4.0. Para examinar a los procesos afectados por la red de producción global se utiliza la herramienta Mapa de Flujo de Valor. El objetivo es identificar oportunidades de mejora en términos de control de procesos.

Se utiliza un Modelo de Madurez Industria 4.0 que incluye la perspectiva del proveedor (evalúa a todos los proveedores en la red) y la perspectiva de la red que analiza los niveles de madurez I4.0 de la red como un todo. El foco está en mejorar la calidad del proveedor en términos de sus procesos sin considerar explícitamente la mejora de los productos en términos de usabilidad o valor para el cliente.

Para las debilidades identificadas se pueden analizar sus causas y estructurar dicho análisis utilizando un diagrama de Ishikawa.

Conceptualización. En base a la etapa de análisis, en esta fase tiene como objetivo desarrollar el concepto para un caso de uso I4.0 que contribuya a la resolución del problema seleccionado considerando sus causas. En esta etapa se realiza un taller cuya agenda incluye una motivación para la implementación de I4.0, la presentación de los resultados de las etapas anteriores, un espacio creativo en el cual todos los participantes contribuyen con ideas para resolver el problema en base a I4.0, y la conceptualización del caso de uso.

Realización. La implementación de la solución I4.0 depende de la adquisición de tecnología o know-how a un tercero. Esta etapa da apoyo a la especificación de requerimientos, análisis de potenciales proveedores hasta la selección del proveedor.

Demostración. Esta etapa pretende documentar el caso de estudio a efectos de que sirva de inspiración para otras áreas o empresas.

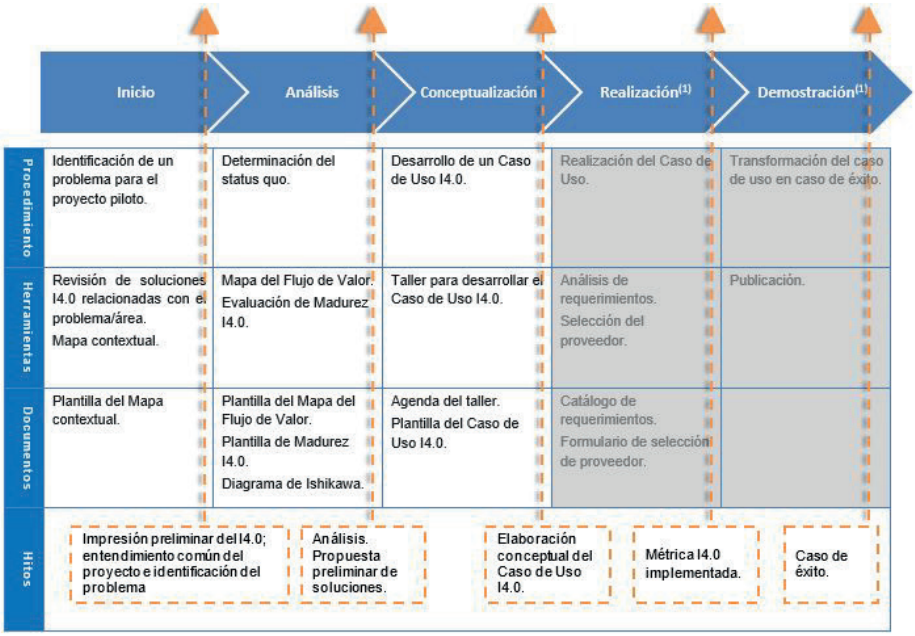

Fig. 1. Etapas para el desarrollo de un caso de uso para implementar una solución basada en Industria 4.0. (1) Etapas no cubiertas en este proyecto. Fuente: Basado en la propuesta de [9].

4 Avance del proyecto

El proyecto se encuentra en la etapa inicial para lo cual se trabajó en un relevamiento preliminar de los procesos. En forma paralela, también se avanzó en la evaluación de la madurez de uso de las tecnologías de Industria 4.0 en la industria estudiada.

En primer lugar, para describir los procesos productivos se entrevistó al Gerente de Producción (entrevista virtual), quien comentó que la elaboración de productos radica principalmente en tres líneas productivas a las cuales denominan de la siguiente manera: Línea 1 (L1), Línea 3 (L3) y Línea 4 (L4). Las mismas son utilizadas de la siguiente manera:

- Línea 1, utilizada principalmente para producir calibres chicos en plástico (PET) de 500 cc, vidrio descartable de 237cc, agua con y sin gas.
- Línea 3, es utilizada para la gaseosa Retornable, tanto en formato vidrio como REF PET.
- Línea 4, la más nueva y tecnológica, utilizada principalmente para calibres más grandes.

La separación de formatos chicos con los grandes entre las líneas 1 y 4, se debe a una cuestión de eficiencia productiva. Esto radica en que, como se menciona anteriormente, la L4 es más nueva, más veloz y mucho más eficiente, con lo cual un lote de calibre inferior se produce mucho más rápido, necesitando realizar muchos cambios en poco tiempo entre un producto y otro (ocurriendo lo contrario en L1).

A continuación, se incluyen las especificaciones generales de cada línea, a fin de detectar problemas potenciales o actuales en los distintos procesos. Las partes integrantes de Línea 1 según el proceso de producción son:

1. Sopladora (ingresan las preformas y salen las botellas).
2. Etiquetadora.
3. Transporte aéreo (lleva la botella etiquetada hasta la entrada de la llenadora a gran velocidad a fin de enfriar el plástico).
4. Llenadora (aquí comenta el gerente que existe un "cuello de botella").
5. Capsuladora (coloca la tapa).
6. Inspectora de llenado.
7. Codificadora.
8. Horno y empaquetadora.
9. Paletizadora.

El punto más frágil de esta línea en términos generales en el número 4, la llenadora. Aquí ocurre a menudo un cuello de botella, y es donde, tanto lo que ingresa a la llenadora como todo lo que sale ocurre en un tiempo más rápido que el proceso de llenado. Otra dificultad -además del tiempo que insume la llenadora- es la temperatura, debido a que la bebida que ingresa en las botellas debe estar a una temperatura de 4° C, y para esto, debe existir un equipo con torres de enfriamiento combinada con la utilización de Glicol para obtener la temperatura requerida de manera constante.

El tipo de llenado utilizado en esta línea es Isobárico, es decir, se deben cambiar los picos dependiendo del calibre o sabor a llenar. Esto último insume tiempo entre las distintas producciones. Además, para el formato 237cc que son de vidrio descartable, la tapa utilizada es estilo corona y no plástica como ocurre con el resto de las botellas, con lo cual, adaptar el sistema de capsuladora también demanda tiempo extra de trabajo.

Por último, la sanitización de toda la línea antes y después de una producción es extremadamente sensible e insume mucho tiempo, conocida comúnmente como "CIP" (por sus siglas del inglés Cleaning In Place).

La línea 4 tiene componentes similares para efectuar el proceso productivo, desde la sopladora hasta la paletizadora, salvando algunas diferencias:

- El proceso de llenado es volumétrico en L4 (a diferencia de L1 que es isobárico), con lo cual no se requiere cambiar picos y demás partes de la llenadora al momento de cambiar el sabor o calibre.
- La temperatura de llenado en L4 es de 15 °C y en L1 es de 4° C.

- L4 produce 40.000 litros por hora de producto terminado con 8 personas por turno mientras que L1 produce aproximadamente 15.000 litros por hora con la misma dotación por turno.
- La tecnología utilizada en L4 es superior. La paletizadora es un robot más veloz que manipula y acomoda los paquetes previos al armado del pallet completo.

Respecto a la línea L3, aquella destinada a la producción con envases retornables, es una línea del año 2010, la cual produce un 85% con botellas de plástico (REF PET) y un 15% con botellas de vidrio. Al igual que la línea 1 de producción, el llenado se hace con una metodología isobárica (se desconoce si existe sistema volumétrico para líneas retornables). Las partes de la línea de producción son similares a las de las líneas anteriores, con la diferencia de que no cuentan con una zona de soplado. Los procesos adicionales que se suman son los siguientes:

- Desencajonadora (al principio) que es la que quita las botellas de los cajones.
- Destapadora se encarga de quitar las tapas de las botellas que la tienen puesta.
- Cadena transportadora con sensores para detectar olores o líquidos fuera de especificación (descartando automáticamente los envases que no se encuentran en condiciones óptimas).
- Lavadora industrial para higienizar las botellas.
- Llenadora.
- Encajonadora (al final) coloca las botellas llenas en los cajones plásticos.
- Paletizadora.

Es una línea “más lenta” en términos de producción, tiene una demanda productiva de alrededor de 25000 litros por hora aproximadamente (funcionando de manera constante) y requiere por lo menos entre 10 y 12 personas para monitorear y llevar a cabo el proceso de elaboración.

El CIP y cambio de picos es un proceso muy lento, y demora algunas horas poder dejarla en condiciones para cambiar el sabor o calibre de la siguiente producción.

En resumen, los problemas claves detectados durante las primeras entrevistas y la observación directa son los siguientes:

- Llenadoras: en alguna línea es muy lenta, sea por método de llenado o por la lentitud en hacerlo. Se debe considerar que, si este punto se logra realizar de manera más rápida y eficiente, se requerirá que tanto los pasos anteriores como los posteriores a la llenadora, también tendrán que aumentar su eficiencia para que el cuello de botella no se genere en otro punto de la línea.
- Temperaturas de llenado: La línea 1 requiere temperaturas muy bajas para su llenado. En otras plantas de la misma subsidiaria existen las llamadas líneas Hot Fill (llenado en caliente) aunque a veces depende del tipo de producto a envasar.
- Falta de versatilidad para cambiar de sabores o calibre rápidamente ante demandas decrecientes, recesión y pérdida de poder adquisitivo, donde los lotes de producción deben ser más cortos.

– Sanitización: demanda mucho tiempo lo cual conlleva a mayores costos.

Con respecto a la madurez, solo evaluamos como primera instancia, lo que respecta a la Producción utilizando la herramienta propuesta por Peukert et al. [9]. Esta evaluación, realizada en conjunto con supervisores de producción, integrantes del área logística y un encargado de Cadena de Suministros, pretende diagnosticar cómo se pueden optimizar procesos productivos y de qué manera se podrían reducir costos de producción con la ayuda de Industrias 4.0. El trabajo propuesto por los autores estructura el análisis en seis temas o dimensiones para el sector de Producción: procesamiento de datos en la producción, comunicación máquina-máquina (M2M), redes empresa y producción, infraestructura de Tecnologías de la Información y la Comunicación (TIC) en la producción, interfaces hombre-máquina y eficiencia con pequeños lotes. Se utiliza una escala de cinco niveles (1-5), considerando a 5 como el nivel más alto de madurez respecto a dicho nivel (ver Fig. 2).

Madurez Industria 4.0 – Producción					
Procesamiento de datos en la producción	No hay procesamiento de datos	Almacenamiento de datos para documentación	Análisis de datos para monitoreo de procesos	Evaluación para planificación de procesos/control	Planificación automática de procesos/control
Comunicación M2M	No hay comunicación	Interfaces field bus	Interfaces ethernet industriales	Las máquinas tienen acceso a internet	Servicios web (software M2M)
Red entre la empresa y producción	No hay red entre producción y otras unidades de negocio	Intercambio de información vía correo/telecomunicación	Formatos de datos uniformes y reglas para el intercambio de datos	Formatos de datos uniformes y servidores vinculados entre divisiones	Soluciones TI totalmente en red
Infraestructura TIC en producción	Intercambio de información vía correo/telecomunicación	Servidores de datos en producción	Portales basados en internet con datos compartidos	Intercambio de datos automatizado (e.g. traza de pedidos)	Proveedores/clientes totalmente integrados en el proceso de diseño
Interfaces hombre-máquina	No hay intercambio de datos entre usuario y máquina	Uso de interfaces locales	Monitoreo/control de producción centralizado/descentralizado	Uso de interfaces móviles	Realidad aumentada y asistida
Eficiencia con pequeños lotes	Sistemas de producción rígidos y una pequeña proporción de partes idénticas	Uso de sistemas de producción flexibles y partes idénticas	Sistemas de producción flexibles y diseños modulares para los productos	Producción basada en componentes, flexible de productos modulares dentro de la compañía	Producción basada en componentes, modular en redes que agregan valor

Fig. 2. Evaluación de madurez de para el caso analizado respecto a tecnologías 4.0. Fuente: Elaboración propia utilizando la herramienta propuesta por [9].

La interpretación de estos niveles en el caso de Aguas y Gaseosas bajo estudio se puede resumir de la siguiente manera: respecto al Procesamiento de datos en la producción, se encuentra en el nivel 4, llamado “Evaluación para planificación de procesos/control” debido a que los datos recabados en la operatoria de producción son nucleados por un sistema para que puedan analizarse de manera conjunta, a fin de mejorar la eficiencia productiva de los planes sugeridos por el área de Planeamiento. En cuanto a la Comunicación M2M, se puede apreciar que se encuentra entre el nivel 3 y 4 (se tomará un valor intermedio de 3,5). Esto se debe a que no todas las partes de la línea de producción tienen acceso a internet, pero se encuentra intercomunicadas entre sí, a fin de lograr un flujo constante de la información sobre la producción. El acceso a internet existe en todas las partes de la línea, la mayoría tiene PC y existe una

red WIFI en la nave. Aunque no todas las máquinas se encuentran conectadas a internet, pero se está trabajando en eso por cuestiones de ciberseguridad.

Las Redes de la empresa y la producción, se puede evaluar con un nivel 2,5, principalmente porque no existe un sistema único de comunicación que sirva sinérgicamente para implementar un proceso productivo y administrativo. Esta dificultad probablemente radique en la utilización de múltiples sistemas para diferentes tareas, complementadas con la utilización del correo electrónico.

Respecto a la infraestructura TIC, se encuentra en un nivel 4 según datos recabados en la entrevista con especialistas del área. Muchos datos son compartidos con un sistema ERP, otros son apreciados solo en cartelería o compartidos en reuniones, lo cual genera un replanteamiento si este nivel estaría correcto o si su madurez en este punto es inferior.

Las Interfaces Hombre-Máquina permiten que en cada proceso se pueda llevar a cabo un monitoreo de la situación de manera descentralizada a través de ordenadores y en algunos casos la utilización de dispositivos Handheld. En primera instancia, se consideró que el valor 4 sería apropiado para este nivel.

Por último, se encuentra le Eficiencia de Pequeños Lotes, ubicándose en el nivel 3 de madurez, debiéndose esto último a la gran capacidad y velocidad de respuesta frente a la necesidad de adaptarse a un cambio repentido de producción. Por ejemplo, cuando se produce un cambio de calibre, sabor o detección de bebida no apta, con necesidad de realizar un rápido descarte/separación para realizar un analizar por el laboratorio.

A modo ilustrativo, y con el fin de observar el potencial en base a la mayor o menor madurez respecto a cada nivel en el ámbito de Producción, se desarrolló un gráfico radial para ver donde se debe apuntar en principio para atender los problemas inmediatos o potencialmente inminentes (ver Fig. 3).

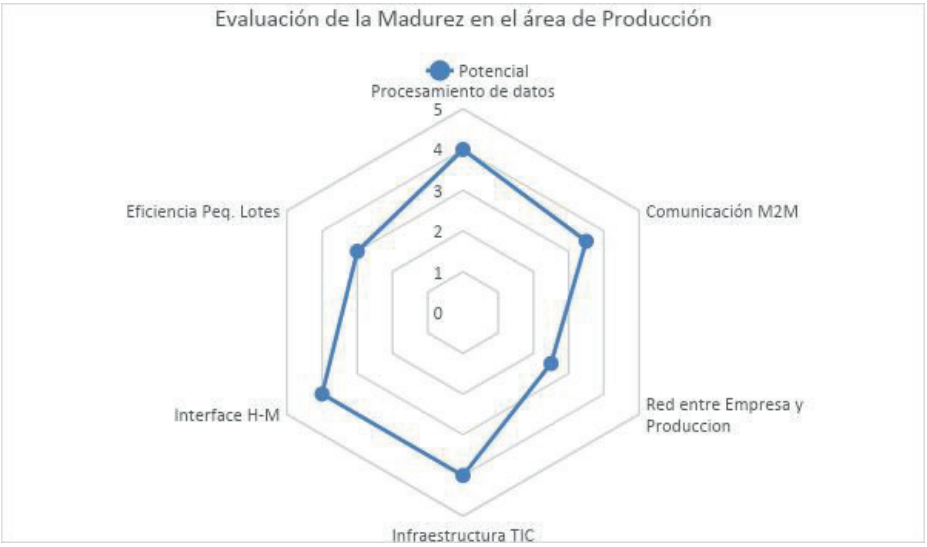

Fig. 3. Gráfico radial que representa la evaluación de madurez y evidencia el potencial según la madurez de la producción, basado en la propuesta de [9]. Fuente: Elaboración propia.

5 Conclusiones

La aplicación del modelo planteado por los autores en este tipo de industrias no es muy conocido, con lo cual, a pesar de que la investigación se encuentra en sus inicios, se avizora la posibilidad de poder recabar información necesaria para lograr un estudio de caso certero que marque un precedente para trabajos similares. Las tecnologías de I4.0 serán fundamentales para que las empresas del rubro consumo masivo, desarrollen ventajas estratégicas respecto a sus competidores. Se está trabajando en el proyecto contemplando no solo los pasos a seguir por el modelo, sino también principalmente atendiendo las necesidades de la compañía bajo estudio. Esto se logrará mediante al acceso a la información como anteriormente se menciona, pero también gracias a la buena predisposición de las distintas áreas de la empresa que se interesan en colorar para que la investigación pueda llevarse a cabo de la mejor manera posible. Esto último permitirá impulsar el potencial de este trabajo como una herramienta eficaz al momento de solucionar problemas con tecnologías 4.0.

La primer fase del trabajo permitió detectar problemas que son considerables desde el punto de vista económico, y que, en economías en retracción como la actual donde los costos son un punto crítico al momento de valuar un resultado, es alentador poder avanzar con una investigación en la cual, aunque sea de modo tentativo, queden planteadas las bases donde se explique cómo una inversión en este tipo de tecnología que permita acercar a la compañía a una Industria 4.0 puede reducir notablemente los costos y mejorar la eficiencia productiva y logística.

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La pandemia como oportunidad para reinventarse

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Breve reseña de la empresa

Francisco Lonas SRL es una empresa bahiense que desde hace 30 años sostiene una constante evolución de calidad y alto compromiso en sus servicios en el mercado de la fabricación de Big Bags, Protección Solar y Lonería Industrial. Fue fundada el 4 de febrero del año 1991 por Ariel Rodríguez, Darío Rodríguez y Francisco Speratti.

Su trayectoria y experiencia le permite brindar un servicio de excelencia, ofreciendo productos de calidad a un precio competitivo junto con un asesoramiento acorde a las distintas necesidades del mercado.

La firma es la primera y única fábrica de Big Bags del sur argentino, con proceso de fabricación bajo norma ISO:9001 de Calidad e ISO:21898 en Labordata (Alemania).

Su principal objetivo es brindar un servicio integral de confianza, garantizando la entrega en tiempo y forma. Brinda una rápida respuesta a sus clientes, poniendo a su disposición una planta fabril de 2500m2.

Problemática detectada

Debido a la caída de las ventas y el desajuste en la cadena de pagos, la firma se vio obligada a tomar las medidas propuestas por el Estado, como créditos a tasa 24%, el programa de asistencia de emergencia al trabajo (ATP), moratoria impositiva al 30/07/2020, etc.

Sin embargo, independientemente de la situación económica complicada que atraviesa como el resto de las empresas en el país, Francisco Lonas SRL asumió importante compromiso a nivel social. Es por esto que, ante la situación de pandemia, decidió realizar un importante aporte en busca de soluciones prácticas e innovadoras en el ámbito de la salud.

Solución implementada

Dadas las maquinarias y el personal capacitado que posee la empresa, junto con el asesoramiento del personal sanitario, se realizaron diferentes elementos para la prevención del contagio del Covid-19:

1. Cortinas divisorias para terapia intensiva e intermedia (Hospital Municipal, Hospital Italiano).
2. Barbijos para fuerzas de seguridad (Policía de la Provincia).
3. Máscaras de protección facial impresas en tecnología 3D.
4. Cabina de traslado para pacientes Covid con una atmósfera controlada de presión negativa y filtros HME en la salida (a pedido de Rotary Club Bahía Blanca).
5. Delantales para personal de salud de los hospitales Municipal de Bahía Blanca, Italiano de Bahía Blanca y Austral de Buenos Aires.

Por otra parte, junto con la comunidad profesional del sistema sanitario de la ciudad, como así también ingenieros y profesores de la UNS, se desarrolló el "CASCO CPAP Bahía Blanca". Es un casco Helmet de VNI (Ventilación No Invasiva) ya existente desde los años '90, para tratamiento de pacientes Covid, con excelentes resultados. Dicho desarrollo fue expuesto en el Consejo Deliberante de la Ciudad, quien presentó el proyecto de declararlo de Interés Municipal, mientras se cumplen todos los pasos de presentación a ANMAT para su aprobación.

Resultados obtenidos:

El desarrollo y la producción de los elementos anteriormente mencionados permitió a la empresa reinventarse y de esta manera mejorar la situación económica y financiera. Además, la participación activa en la lucha contra el COVID 19 generó gran orgullo y reconocimiento en todo el personal. Cabe destacar que los excelentes resultados fueron tanto a nivel local como fuera de la ciudad (Hospital Austral, Hospital Posadas, Hospital Garraham, entre otros).

Comentarios finales

Si bien la situación económica no era la mejor, la empresa pudo reinventarse en una situación de pandemia, y a su vez, de esta manera, hizo un aporte social colaborando activamente contra la lucha del Covid-19. Las capacidades técnicas y creativas de la firma fueron puestas al servicio de nuevos productos necesarios para la situación crítica de salud que atravesó la población. "El mundo que tendremos será el que seamos capaces de lograr "

Documentos fotográficos















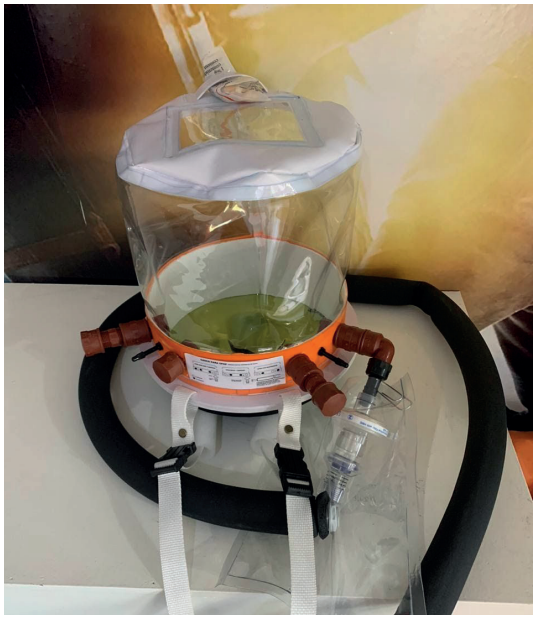

Simulación de un proceso Inbound Freight de Estados Unidos de América hacia las ciudades de Saltillo y Toluca como herramienta para la evaluación y mejora de los procesos en Facil N. A. de México

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Abstract

El proceso de Inbound Freight en un proveedor de servicio completo representa un área de oportunidad para reducir costos principalmente por las discrepancias generadas de origen por los proveedores, inducidas por las operaciones del agente aduanal, o producidas durante el transbordo de material en la frontera y el costo de mantener inventario con el agente aduanal. El presente trabajo proporciona la descripción de un proyecto de modelado y simulación para la comparación del proceso actual de Inbound Freight, con un modelo de operación propuesto por el equipo de Comercio de Exterior de Facil NA México, dicha propuesta se desarrolló con la finalidad de los reducir costos relacionados medidos a través de un indicador de desempeño que de manera consistente se reporta por debajo del valor meta, ambos procesos, son modelados e implementados en CPN Tools, los resultados de la simulación permiten la estimación de las discrepancias esperadas en ambos casos, información base que permite la evaluación de sus desempeño para facilitar la toma de decisión de alta dirección de la organización.

Keywords: Medición y mejora de procesos, Simulación basada en eventos discretos, CPN Tools, Dirección de Operaciones, Logística y Transporte

1 Introducción

Diversas investigaciones académicas se centran en los problemas de la cadena de suministro en la industria del automóvil, específicamente en la reducción en el costo logístico, sin embargo, poco se ha discutido sobre la reducción de costos de logística de entrada de la industria automotriz mexicana (Blaga & Jozsef, 2014). La necesidad de desarrollar este proyecto surge a partir de la información y experiencia acumulada en el equipo de gestión de la cadena de suministro, de la empresa Facil NA de México, un proveedor de servicio completo de sujetadores (Compras, Logística, Calidad e Ingeniería). El equipo de gestión de la cadena de suministro ha
tenido la oportunidad de reconocer además de examinar los problemas y dificultades de primera mano considerando el proceso actual, no obstante, no se cuenta con una herramienta que permita el análisis y estimación de los resultados un proceso modificado. Desde el punto de vista estratégico, a partir de la revisión gerencial de los indicadores clave de desempeño (KPIs), se observó que los costos logísticos de la empresa han mantenido la tendencia a superar los valores objetivo, lo que ha influido en el rendimiento operativo, así como en las ganancias de la cadena de suministro. A partir de la medición del Inbound Freight cost (Costo de transporte de entrada) como KPI para los valores simulados de ambos procesos (actual y propuesto), se buscará valorar el impacto esperado del proceso modificado, además se prevé como impacto extendido (inherente a la modificación propuesta) la reducción de tiempos de operación.

2. Diagnóstico y objetivos.

Problema: El Indicador clave de desempeño de transporte de entrada ha estado fuera de objetivo durante doce meses porque ha superado la meta de 4.0% con respecto a las ventas, utilizando a Facil NA de México como caso de estudio.

2.1 Objetivo general.

Desarrollar los modelos de simulación como herramienta para la comparación del desempeño de ambos procesos en términos del KPI seleccionado, para determinar qué proceso es mejor y en qué proporción genera mejores resultados. La propuesta de rediseño será evaluada mediante la implementación de modelos de simulación para

estimar los resultados esperados.

2.2 Objetivos particulares:

- Establecer diferencias de costos de Transporte y Almacenamiento, entre el actual sistema de transporte con trasbordo versus un sistema sin trasbordo.
- Analizar todas las variables operativas actuantes a efectos de plantear modificaciones que posibiliten el cambio del flujo de información permitiendo una mayor visibilidad en la cadena de suministro desde el OEM, retailers hasta los proveedores.
- Ejecutar los análisis de los procesos de acuerdo con el Sistema de mejora continua para el problema de transporte.

2.3 Definición de KPIs y métricas de desempeño

Según el Grupo Aberdeen, el Inbound Freight puede consumir el 40% del gasto promedio una organización de flete anual o 3.6% a 5.2% de las ventas anuales totales de una empresa. El KPI para este caso de estudio es *Inbound Freight* que lo podemos definir como el costo del abastecimiento, agilización y recepción de bienes, que está llegando a la organización.

Operacionalmente, el KPI *Inbound Freight* es calculado como el porcentaje de los gastos totales del transporte de entrada entre las ventas mensuales. En ambos casos (operación actual y propuesta) aplica a todo el gasto facturado y el objetivo es de 4.0% mensual, como referencia del desempeño en esta métrica, en la tabla 1 se observa los resultados del año 2019, como puede verificarse con estos datos, sólo en 3 meses de los doce, se registraron valores dentro del objetivo o por debajo (lo que implica una operación más eficiente aún), pero 75 % de las veces el desempeño supero el valor máximo establecido como objetivo. El sistema de calidad de la compañía indica que si el indicador no es alcanzado debe realizarse una acción correctiva, pero al momento las actividades desarrolladas no han sido efectivas por lo que se desarrolló una propuesta de proceso modificado con el cuál se busca la reducción de costos en el transporte de entrada, de tal forma que se definió como necesario la aplicación de herramientas de modelado y simulación para verificar el impacto esperado de las acciones definidas.

Tabla 1. Resultados del KPI Inbound Freight del año 2019

Mes	**Inbound Freight**		**Mes**	**Inbound Freight**	
	Real (%)	**Meta (%)**		**Real (%)**	**Meta (%)**
Enero	**4.00**	4.00	**Julio**	**3.30**	4.00
Febrero	4.50	4.00	Agosto	4.30	4.00
Marzo	5.20	4.00	Septiembre	4.20	4.00
Abril	5.10	4.00	Octubre	4.60	4.00
Mayo	4.70	4.00	Noviembre	4.70	4.00
Junio	**3.80**	4.00	Diciembre	4.90	4.00

3. Análisis del proceso y desarrollo de propuesta

o rediseño del proceso 3.1 Situación actual

- Los 4 proveedores más grandes pueden pasar por un proceso logístico diferente al de los suministros más cortos, ver figura 1.

- Las discrepancias son evaluadas por nuestro equipo en WH Toluca / Saltillo, aunque el agente aduanal realizo la misma actividad en días anteriores

- Alto costo: retención, revisión, informe por aduanas, proveedor de transporte. • • • La logística (de EE. UU. A MX) es administrada por el equipo en las oficinas centrales de Norteamérica en Ohio Estados Unidos, pero no tenemos suficiente soporte para resolver problemas.

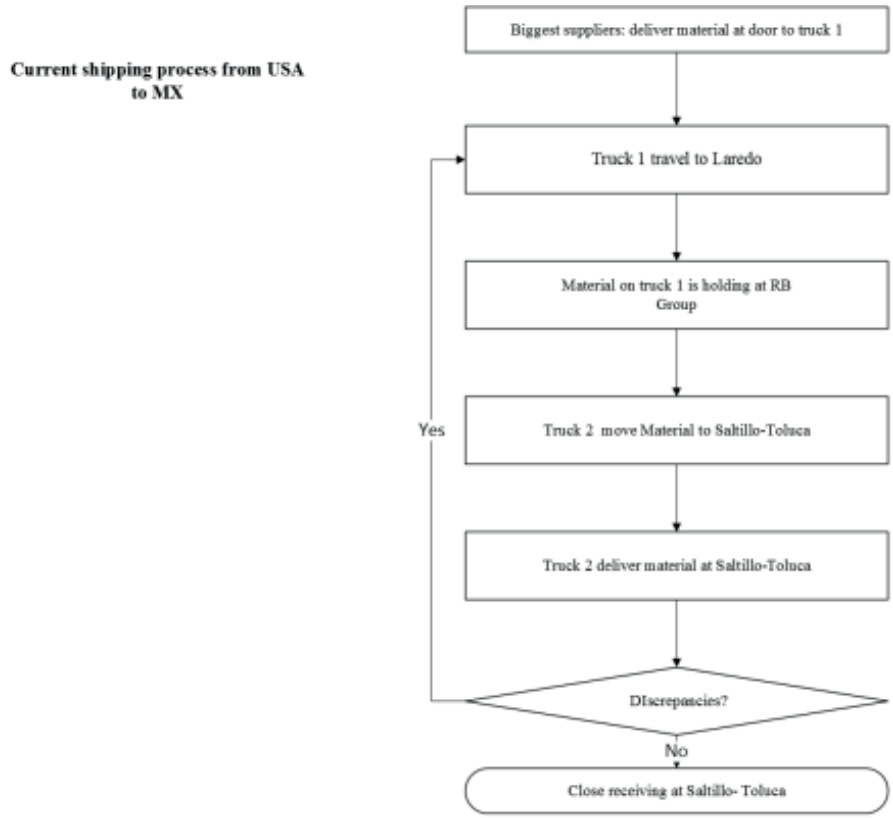

Fig. 1. Diagrama de flujo Proceso actual de logística de entrada

3.2 Situación propuesta

El equipo de comercio exterior de la región Norte América del FSP (full service provider) donde se realiza la propuesta de Re diseñar e integrar la cadena de suministro en el proceso de logística de entrada al identificar que en el proceso de Inbound Freight del año 2019 el costo fue 4.48% el de las ventas anuales de los datos mostrados en la tabla 1, el KPI logística de entrada estuvo 0.48% fuera de objetivo, se detectó el costo de la actividad del agente aduanal actual para los cuatro mayores proveedores de manufactura de la cadena de suministro representaba el 0.53% de las ventas anuales. Después mediante una lluvia de ideas del equipo de comercio exterior detectaron que el proceso de inspección de material en facturas, cantidad y etiqueta se repetía en el agente aduanal y posteriormente en los almacenes de Saltillo y Toluca. De acuerdo con lo anterior, se definieron las siguientes acciones:

• Realizar el proceso sin la inspección del material (factura, cantidad y etiqueta) en el almacén del agente aduanal.

• Analizar el lead time de los cuatro proveedores sin la operación anterior

• Comparar los costos por discrepancias del proceso actual contra

el proceso propuesto. • Evaluar el KPI de Inbound Freight.

• Documentar el proceso de mejora de continua.

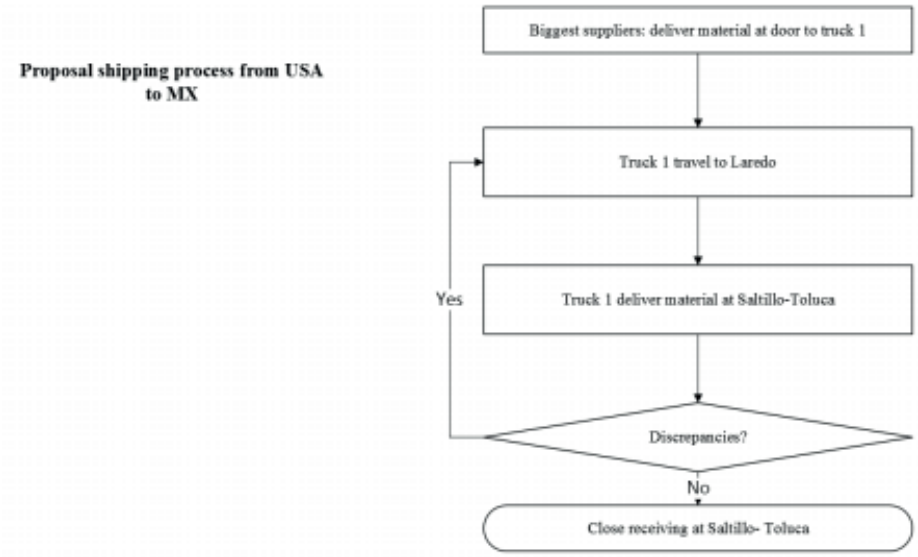

Fig. 2. Proceso propuesto de logística de entrada

4. Simulación como método de estimación de los resultados esperados

El presente proyecto, toma como referencia el trabajo de (Wang & Chen, 2016), donde se combina el sistema logístico real de un fabricante automotriz, utilizando el modelo de red Petri y el software de simulación CPN Tools para simular y proponer un método de optimización efectivo basado en los resultados de la simulación. La simulación como tal es un proceso y en general consta de las siguientes etapas:

- Definición del sistema: Para tener una definición exacta del sistema que se desea simular, es necesario hacer primeramente un análisis preliminar de éste, con el fin de determinar la interacción con otros sistemas, las restricciones del sistema, las variables que interactúan dentro del sistema y sus interrelaciones, las medidas de efectividad que se van a utilizar para definir y estudiar el sistema y los resultados que se esperan obtener del estudio.
- Formulación del modelo: En la formulación del modelo es necesario definir todas las variables que forman parte de él, sus relaciones lógicas y los diagramas de flujo que describan en forma completa el modelo.
- Colección de datos: Es importante que se definan con claridad y exactitud los datos que el modelo va a requerir para producir los resultados deseados.
- Implementación del modelo en la computadora: Con el modelo definido, el siguiente paso es decidir si se utiliza algún lenguaje para procesarlo en la computadora y obtener los resultados deseados. • Validación: A través de esta etapa es posible detallar deficiencias en la formulación del modelo o en los datos alimentados al modelo.
- Experimentación: La experimentación con el modelo se realiza después que éste haya sido validado. La experimentación consiste en generar los datos deseados y en realizar un análisis de sensibilidad de los índices requeridos.
- Interpretación: En esta etapa del estudio, se interpretan los resultados que arroja la simulación y con base a esto se toma una decisión.
- Documentación: Dos tipos de documentación son requeridos para hacer un mejor uso del modelo de simulación. La primera se refiere a la documentación del tipo técnico y la segunda se refiere al manual del usuario, con el cual se facilita la interacción y el uso del modelo desarrollado.

5. Modelado y simulación

5.1 Descripción proceso actual

Para el desarrollo de los modelos, se emplean las Redes de Petri Coloreadas (RPC's), formalismo para la simulación basada en eventos discretos aplicable a sistemas de manufactura y logísticos (Piera, 2004).

A continuación, se describe el modelo del proceso actual, implementado en CPN Tools (Figura 3). El total de órdenes a simular, provenientes de los cuatro proveedores, se hallan contenidas en un nodo lugar del tipo "source" denominado "Ordenes totales", la información sobre la distribución de las órdenes por cada proveedor A, B, C y D, quienes envían determinadas ordenes de acuerdo al ERP existente en la cadena de suministro en un FTL (Full Truck Load) hacia la frontera en Laredo, Texas USA donde se realiza un proceso de cruce de frontera de USA a México, se indican en el modelo a través de los valores en los nodos lugar "DistProveedores Saltillo" y "DistProveedores Toluca", información obtenida a partir del análisis de los datos históricos, para ambos nodos lugar se mantiene la siguiente equivalencia de los valores A= 1, B= 2, C=3 y D=4, para identificar a cada uno de los proveedores, y la variable que se emplea es P.

La información referente a la distribución desde cada proveedor hacia cada destino (Saltillo o Toluca), es de manera similar obtenida mediante la revisión de los valores registrados en el año anterior, dicha información se suministra en el nodo lugar "DistDestinos", en este caso Saltillo se denota con el número 1 y Toluca con el número 2, en tanto la variable empleada es la letra D.

Las transiciones (rectángulos) corresponden a la acción o evento de similar una orden con su correspondiente origen y destino, es decir la asignación de los valores de P y D, cada una de las órdenes procesadas se registra en el nodo lugar "OrdenesDespachadas", dicha información se suministra para la siguiente operación, denominada "Inspección AA", la información histórica de las discrepancias de origen atribuibles a los proveedores se introducen en el nodo lugar "Discrepancias Proveedores", en donde para cada proveedor se tiene la probabilidad de generar discrepancias, dicha información de tiene clasificada para cada combinación (P,D), la variable que simula la existencia o no de una discrepancia es el dígito que se asigna a la letra Q, variable binaria con 0 para el caso de no existir discrepancia y 1 para el caso de existir discrepancia.

En función del destino de cada orden, el flujo se distribuye hacia el nodo lugar "Entrada Cedis Saltillo" si D=1, y hacia "Entrada Cedis Toluca", en el caso D=2. En ambos nodos se almacenan las órdenes procesadas hasta ese punto, las cuáles serán introducidas en la operación de inspección por la empresa en cada uno de los Centros de Distribución (Cedis), cada inspección está indicada como una transición

independiente, dicha operación se simula con la información correspondiente al desempeño histórico observado para el agente aduanal (AA) respecto a las discrepancias inducidas en cada orden, información contenida en el nodo lugar "DistDiscrepancias AA", que de manera análoga a las discrepancias de origen, se tiene clasificada para cada origen, el valor que se asigna para las discrepancias inducidas es indicado por la variable I, que adopta de manera análoga valores 0 y 1, tal como se definió para los valores de Q.

Finalmente, las órdenes libres de discrepancias (con Q=I=0) se depositan en el nodo lugar "Ordenes OK Saltillo" y "Ordenes OK Toluca", según corresponda, complementariamente las órdenes que durante la simulación, recibieron valores 1 en las variables Q o I, son depositadas en los nodos lugar "Ordenes Discrep Saltillo" y "Ordenes Discrep Toluca" Todas las ordenes ok forman parte del inventario disponible y visible para venta en la cadena de suministro por otra parte las ordenes con discrepancias representan inventario que no será visible para venta para la cadena de suministro. En el caso del proceso modificado (Figura 4), el modelado es equivalente, con la evidente diferencia de que se ha suprimido la "Inspección AA", por lo que ahora después de la simulación de la distribución de las órdenes (asignación de valores de P y D, se realiza operación de inspección en los Cedis y se clasifican las órdenes de acuerdo con el atributo de calidad Q exclusivamente.

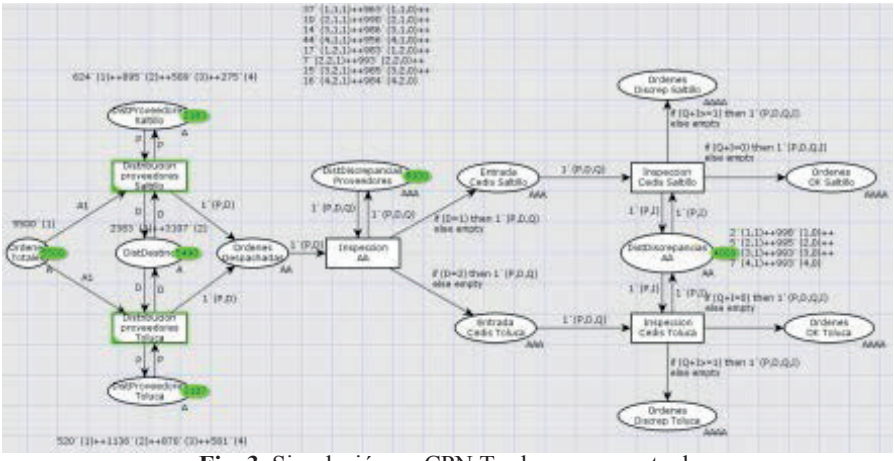

Fig. 3. Simulación en CPN Tools proceso actual



Fig. 4. Simulación en CPN Tools proceso propuesto

6. Resultados

Con el objetivo de obtener datos estadísticos para facilitar la toma de decisión de la alta dirección de Facil NA de México, se realizaron 30 experimentos de ambos procesos, simulando en cada experimento un total de 5500 órdenes, volumen equivalente a un año de operación. En la figura 5 aparecen los resultados simulados para el proceso actual de logística de entrada donde el material es inspeccionado por el agente aduanal lo cual genera discrepancias adicionales a las del proveedor.

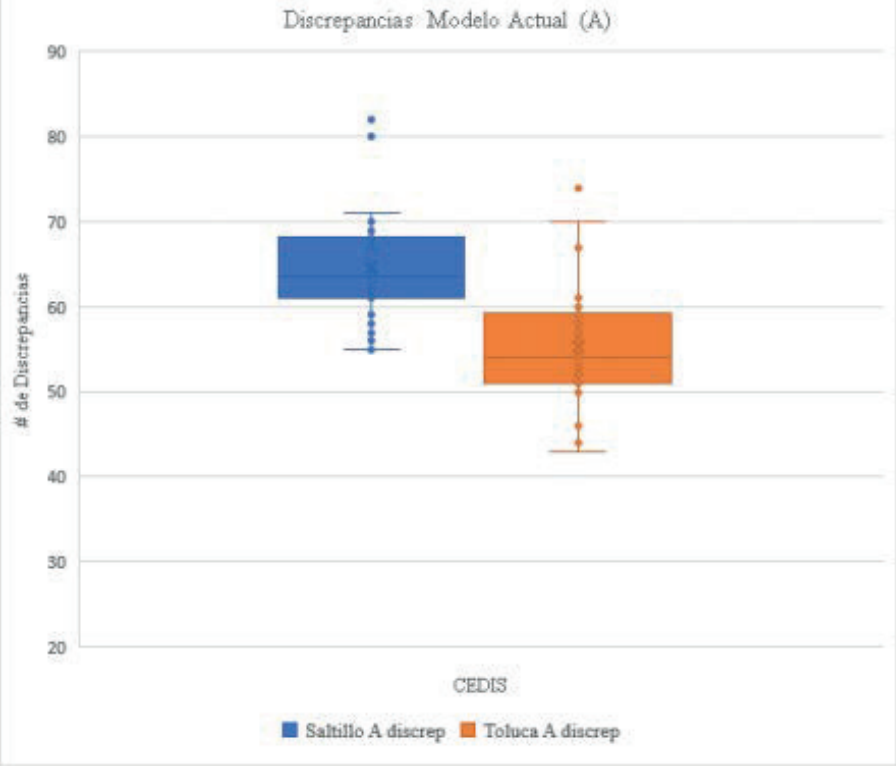

Fig. 5. Número de discrepancias actuales en la sucursal de Saltillo y Toluca.

Como se puede observar en la sucursal de Toluca, considerando el proceso actual, recibe una media de 53 órdenes con discrepancias y la sucursal de Saltillo se recibe una media de 63, a partir de revisar el rango de valores obtenidos, observamos que los valores están entre 43 y 74 casos anuales para el caso de Toluca, en tanto Saltillo reciben entre 55 y 82 órdenes con discrepancias.

De manera análoga, para la simulación de los valores empleado el proceso modificado, se registran los valores obtenidos para los 30 experimentos, en la figura 5 los datos muestran que el modelo modificado propuesto, representa una reducción en los valores del número de órdenes con discrepancias, 59 casos en el escenario máximo para ambas sucursales y en el caso mínimo en 30 para Saltillo y 32 para Toluca. Si hacemos una comparación de los valores medios, también muestran una reducción, 47 órdenes para el sitio del norte de país y 42 órdenes para el centro de distribución del segundo sitio. Otro aspecto mostrado en la figura 3 es el cambio a un proceso lean donde se eliminarían operaciones que no agregan valor porque generan costos de tiempo de

inspección, movimiento de material, transporte y costos de mantener inventario en las instalaciones del agente aduanal.

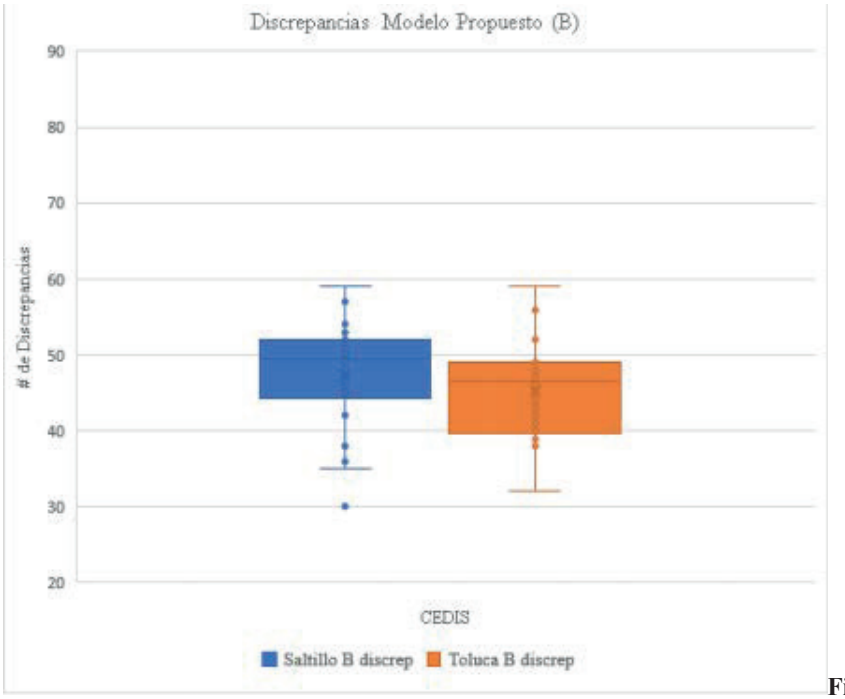

Fig. 6. Número de discrepancias simuladas en la sucursal de Saltillo y Toluca.

7. Conclusiones

El presente documento ofrece datos estadísticos para la toma de decisión del cambio de proceso de Inbound Freight en la empresa Facil NA de México, indicador que esta fuera de objetivo por el costo de esta operación. Los resultados de los 30 experimentos muestran una reducción de órdenes con discrepancias anuales promedio de 65 a 47 casos para la sucursal de Saltillo y de 55 a 42 para Toluca, valores que representan una potencial reducción de 37% y 23 % respectivamente.

La implementación del modelo propuesto implica una reducción directa de costos porque el agente aduanal cobra por cada factura inspeccionada, físicamente (pallet/caja) y administrativamente (errores de cantidad, numero de parte etc. en etiqueta o factura), esta inspección estaría eliminada en el proceso propuesto, así como el mantener el inventario en las instalaciones del proveedor mencionado.

Sin embargo, tal como se evidencia mediante la simulación de desempeño de cada proceso evaluado, la implementación del modelo modificado representa la generación consistente de ahorros operativos y financieros, con la reducción órdenes con discrepancias inducidas por una operación prescindible que no agrega valor y que si agrega tiempos de procesamiento y mermas por errores y fallas en la manipulación de las órdenes por parte del agente aduanal. Complementariamente, existe un beneficio en términos del incremento de la confiabilidad y consistencia de los procesos de abastecimiento (efectividad de las órdenes solicitadas y las realmente disponibles en inventario para la venta), que de manera directa incrementa la capacidad de la empresa para brindar un nivel de servicio competitivo.

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Métodos y modelos de investigación

La Manufactura Aditiva como herramienta clave en la modernización de los procesos de fundición

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Resumen. En el presente trabajo abordaremos una de las tantas posibilidades de la impresión 3D en el campo industrial: la fabricación de modelos patrón para procesos de fundición. Comenzaremos con una breve reseña de los métodos de manufactura clásicos, para pasar a la manufactura aditiva, sus ventajas y desventajas. Luego estudiaremos el procedimiento necesario para la obtención de los modelos, materiales seleccionados, y factores a tener en cuenta. Finalizamos con algunos datos interesantes que se fueron obteniendo con la aplicación de esta técnica y concluimos sobre la aplicabilidad de la misma.

Palabras clave: ingeniería mecánica, manufactura aditiva, impresión 3d, fundición, industria 4.0, procesos industriales.

1 Introducción

Históricamente han existido tres grandes familias de métodos de manufactura bien definidos. Los mismos son: la manufactura extractiva, la manufactura por fundición y la manufactura por conformado. En la década de 1980 surgen las primeras patentes de lo que será la técnica de fabricación moderna, una cuarta que se suma a las anteriores: la manufactura aditiva.

Veremos una breve reseña de las mismas.

1.1 Manufactura Extractiva

Consiste en la remoción sucesiva y controlada de material, partiendo de una materia prima base, hasta obtener la pieza deseada. Ejemplos de este tipo de manufactura son los procesos de mecanizado CNC en los cuales se parte de un “bloque” metálico con sobre material y se lo trabaja por arranque de viruta hasta obtener la pieza deseada.

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Fig. 1. Proceso de mecanizado CNC, técnica de manufactura extractiva.

1.2 Manufactura por Fundición

Consiste en calentar nuestra materia prima hasta fundirla, para luego verter dicho fundente en un molde. Al enfriarse y solidificar, obtendremos nuestra pieza con la geometría del molde en el cual hemos vertido nuestra materia prima.

Este método de manufactura se corresponde a infinidad de piezas de ingeniería en las cuales nuestro fundente es metálico, por ejemplo, aceros o aleaciones de aluminio.



Fig. 2. Proceso de fundición en acero.

1.3 Manufactura por Conformado

La manufactura por conformado consiste en aplicar un esfuerzo mecánico a nuestra pieza para deformarla (conformarla) hasta la geometría deseada, sin aplicación de calor (al menos no hasta el estado líquido de la materia prima). En sí, son procesos basados en la deformación plástica de los materiales. Como ejemplo podemos

mencionar procesos industriales como el estampado de chapas en los cuales, con ayuda de una matriz y una prensa hidráulica, una placa plana de metal adquiere otra forma compleja por aplicación de una gran fuerza mecánica.



Fig. 3. Matriz para estampado de chapas.

Es momento ahora de introducir una cuarta técnica de manufactura, de surgimiento mucho más reciente que las tres anteriores. La misma se conoce como **Manufactura Aditiva**.

1.4 Manufactura Aditiva:

Es una familia de técnicas de fabricación que consisten en la creación de objetos mediante la adición progresiva de material. Por la esencia del método productivo, la manufactura aditiva es un proceso en el cual se minimizan los desperdicios, y mediante el cual se pueden obtener diversas geometrías difícilmente alcanzables mediante métodos de manufactura tradicionales. Su contraparte es la manufactura extractiva. Resulta interesante destacar que estos procesos de manufactura son altamente automatizados, por lo cual suelen no requerir supervisión.

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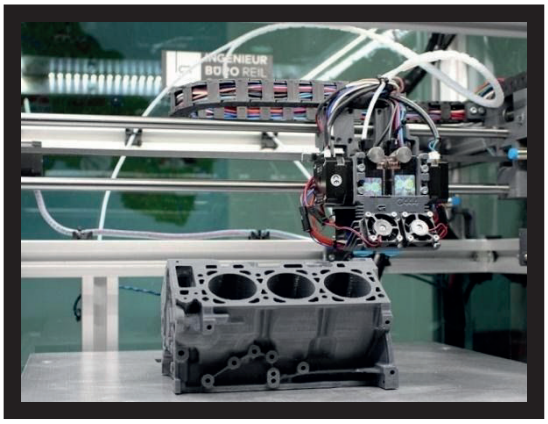

Fig. 4. Impresora 3D, manufactura aditiva.

Como bien se puede concluir del apartado anterior, la impresión 3D es un método de manufactura aditiva que consiste en la deposición controlada de material, hasta obtener cierta geometría deseada.

Si bien existen varias técnicas diferentes de impresión 3D, algo en común en todas ellas es que la creación de objetos se da por la aplicación de sucesivas capas, una tras otra, las cuales hacen que el objeto impreso vaya "creciendo" según cierta orientación. En la presente publicación, haremos referencia exclusivamente a la tecnología FDM, es decir, aquella que se basa en la deposición de polímeros fundidos para obtener piezas.

2 Desarrollo

Como estudio de ingeniería especializado en técnicas de Manufactura Aditiva, una de nuestras principales metas es resolver problemáticas de la industria mediante la aplicación de la Impresión 3D y tecnologías afines. Analizando las necesidades de una empresa a la cual se le brindan servicios, se descubre el enorme cuello de botella que generaba la fabricación de modelos para fundición mediante técnicas tradicionales de tallado manual y mecanizado en madera o aluminio.

Ampliaremos ahora sobre el concepto de Manufactura por Fundición, abordado en la Introducción, para ahondar un poco en los detalles de cómo es el proceso aplicado. Como mencionamos, el hecho de tomar una materia prima, fundirla, y verterla en un molde, es lo que comúnmente llamamos fundición. Si la materia prima es metálica, el método más tradicional consiste en utilizar moldes de arena, en los cuales se genera una impronta con la forma del objeto a replicar y donde se verterá el fundente.

Los metales fundidos no pueden difundir a través de los límites de la arena compactada, por lo cual quedarán "estancados" en esas aberturas hasta el momento en el que solidifiquen y puedan ser retirados.

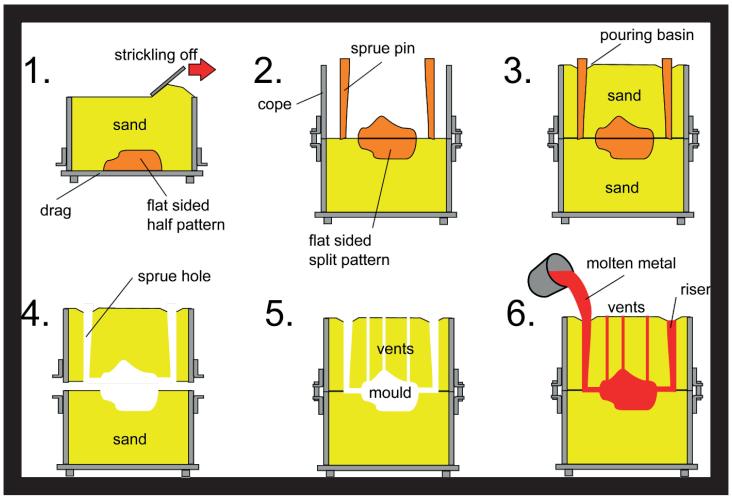

Fig. 5. Proceso de moldeo en arena.

La impronta en la arena se genera a partir de un objeto conocido como modelo, el cual tiene la forma y dimensiones tales que permite la obtención del objeto a fabricar teniendo en cuenta la contracción del material a fundir, sobre materiales para posterior mecanizado, etc. Es decir, cada modelo de fundición debe ser calculado, diseñado y construido de forma anterior al proceso de fundición. Los materiales más utilizados para fabricar estos modelos, son el aluminio y la madera. El primero se suele trabajar con mecanizado CNC, y el segundo se suele utilizar una mezcla entre mecanizado CNC, mecanizado manual y tallado manual, haciendo que sea un trabajo muy laborioso y artesanal. Aquí es donde entra en juego la impresión 3D.

La impresión FDM se basa en 3 elementos principales: una plataforma de impresión en la que se imprime la pieza, una bobina de filamento que sirve como material de impresión y un cabezal de extrusión a través del cual fluye el filamento. En resumen, el filamento es succionado y fundido por el extrusor de la impresora 3D, que deposita el material de forma precisa capa por capa sobre la plataforma. Una vez que la plataforma calefaccionada y el pico del extrusor llegan a las temperaturas configuradas, comienza a extruírse un filamento de material sobre la plataforma a través de una boquilla que se mueve sobre 3 ejes (x, y, z) comandada por un código-G generado previamente en un software de impresión 3D. Al finalizar cada capa, la plataforma se separa del extrusor y comienza la impresión de la siguiente.

Existen diversos materiales para impresión FDM, y tras un análisis técnico se llegó a la conclusión de que, por las cualidades mecánicas, térmicas, y la precisión dimensional, el polímero conocido como PET-G es el ideal para resistir las solicitaciones de los modelos de fundición: Las presiones de la compactación de la arena, y condiciones térmicas levemente adversas por el ambiente en el que se utilizarán.

La implementación de Impresión 3D para la fabricación de estos modelos significó agregar algunas etapas al diseño constructivo de la pieza. Los modelos que antes se construían en una sola pieza, por una limitación tecnológica debían ahora ser

construidos en varios, para luego ser armados, sellados y soldados. Aun así, las ventajas fueron notables desde un primer momento.

Veamos un resumen de las etapas de diseño y fabricación de los modelos de fundición.

1. Análisis de la pieza a fabricar. Todo proceso de construcción de un modelo de fundición, parte del plano de definición de la pieza metálica que deseamos obtener, independientemente del tipo de proceso que se requiera para ello. Aquí debemos tener en cuenta ciertos factores, si existen caras de contacto con otras partes, tratamientos térmicos, o tratamientos de recubrimiento superficial para evaluar las regiones que deberán tener sobre material para posterior mecanizado. Los procesos de fundición raramente se utilizan como método único para fabricar una pieza, sino que son acompañados de otros métodos de manufactura.
2. Diseño del modelo. Basándonos en todo lo analizado en el punto anterior, se ejecuta el diseño del modelo considerando contracciones, ángulos de desmolde, sobre materiales, etc.
3. Modelado 3D del patrón. Utilizando software de diseño asistido por computadora (CAD) generaremos la representación digital del modelo de fundición.
4. Adaptación del modelo para impresión 3D. Aquí partimos del modelo ideal, para dividirlo en las piezas necesarias según la geometría óptima para imprimir, tamaño del volumen de impresión con el que contamos, etc. Además, se incorporan alojamientos y pines de unión para el posterior pegado de las piezas.
5. Laminación. Esta etapa, también conocida como *slicing*, consiste en procesar los modelos 3D obtenidos en la etapa anterior por medio de un software de Impresión 3D, en el cual incorporaremos todos los parámetros que darán las características al modelo físico que obtendremos. Esta es una de las etapas más críticas del proceso.
6. Impresión 3D. En la etapa anterior obtenemos un archivo conocido como *gcode*, el cual contiene las instrucciones codificadas que interpretará la impresora para materializar nuestros diseños. Este proceso puede tardar más de 80 horas, según la complejidad y tamaño de la pieza. Si bien las impresoras 3D son equipos autónomos, la etapa de impresión requiere supervisión constante para detectar fallas, errores y evitar el desperdicio de material en caso de que no se esté ejecutando de forma correcta.
7. Post procesado. Se procede al pegado, ensamblado de los modelos, soldadura de los mismos y rectificado superficial de las zonas de unión entre partes.
8. Verificación. Es importante hacer una verificación dimensional y geométrica de los modelos para asegurarnos de que estén dentro de las tolerancias esperadas y puedan ser utilizados.

A partir de aquí, el proceso de fundición es el mismo que se utiliza desde hace siglos, sin variantes en los equipamientos, los insumos ni las condiciones de trabajo.

3 Conclusión

La implementación de modelos impresos en 3D en los procesos de fundición en arena significaron una disminución de tiempos aproximada del 67%, y una disminución de

costos que ronda el 80% en la fabricación de dichos modelos patrón. Además, se obtienen piezas más livianas que pueden ser operadas por una sola persona, a diferencia de un patrón similar fabricado por ejemplo en aluminio macizo mecanizado.

Respecto a la durabilidad, al día de hoy los patrones fabricados no tienen signos de desgaste luego de 6 procesos de compactación y colada. Se estimó una vida útil de 20 procesos.

Es evidente que la gran ventaja de estos modelos de fundición está en aplicaciones de baja escala de producción. Modelos de aluminio o madera tienen una vida útil estimada de 30 años de trabajo continuo, por lo cual pueden resultar económicamente convenientes frente a la impresión 3D. Sin embargo, dicha inversión inicial es unas 5 veces más elevada lo cual quita flexibilidad a la hora de plantear mejoras en el modelo para mejorar las características físicas, dimensionales y/o de terminación de las piezas a fundir.

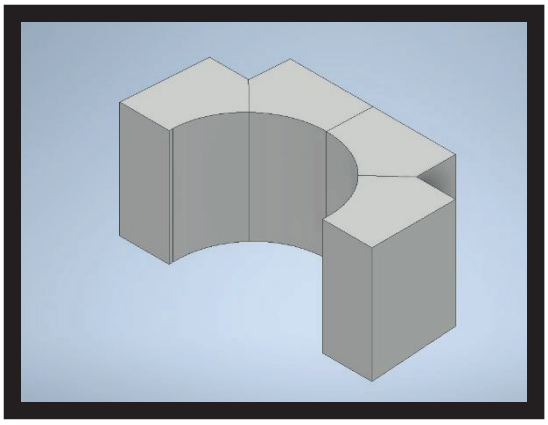

Fig. 6. Diseño CAD del modelo de fundición.

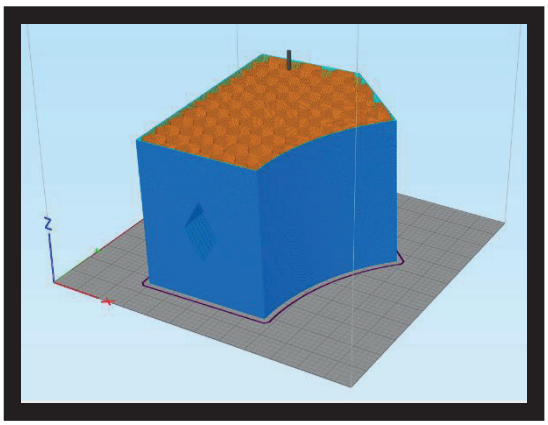

Fig. 7. Laminación de una de las partes del modelo de fundición.

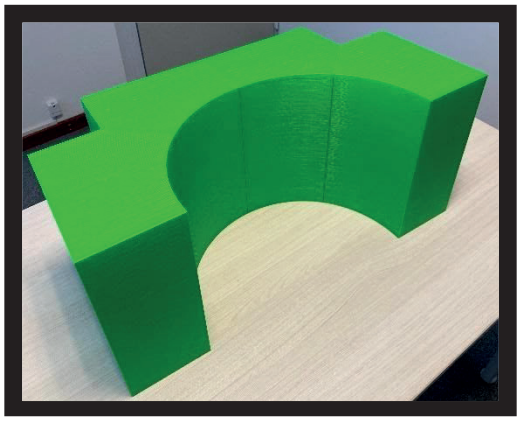

Fig. 8. Modelo impreso en 3D, ensamblado y post-procesado.



Fig. 9. Pieza fundida y mecanizada a partir del modelo impreso.

Optimización de tiempos en Ordenes de Transporte en empresa de servicios petroleros

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Resumen

La mejora continua dentro de las organizaciones es fundamental para la eficiencia y calidad de los procesos. El contexto actual ha puesto sobre la mesa enormes desafíos, sobre todo en el plano tecnológico, donde las comunicaciones eficientes entre los empleados son clave a la hora de mejorar la productividad en las empresas. Re-pensar cómo se trabaja y se procesa la información ha conducido a adquirir cierta elasticidad en los agentes que intervienen en todos los niveles organizacionales con el fin de seguir siendo competitivos dentro de un mercado global muy dinámico. En el presente artículo se aborda la incorporación de una mejora relacionada con el manejo de documentación y los resultados obtenidos. Este proceso corresponde al área de Materiales de la empresa Halliburton Argentina, en colaboración con su proveedor directo, Sea White S.A. La acción de mejora se centró en la gestión de las órdenes de transporte con el fin de optimizar los tiempos en cada una de las etapas que requieren las mismas desde el origen hasta su procesamiento definitivo. Cada eslabón que compone el proceso es vital para alcanzar la excelencia operativa. A través de este trabajo se intenta mostrar como pequeños cambios en el flujo de la documentación producen mejoras significativas en el procesamiento de órdenes de transporte.

Palabras clave: Mejora Continua, optimización, órdenes de transporte.

1. Introducción

El proceso de mejora continua, incorporado por toda una empresa, implica un flujo continuo de innovación [1]. Encuentra aplicación en diversas áreas.

Uno de los conceptos más utilizados e implementados en la industria es el Ciclo de Deming [2] (Fig. 1) conocido como PDCA (Del inglés, Plan-Do-Check-Act) o PHVA (Planificar-Hacer-Verificar-Actuar). Este ciclo es una estrategia basada en la mejora continua de la calidad en cuatro pasos.

- Planificar: Se detecta una oportunidad y se establecen las actividades del proceso, necesarias para obtener el resultado esperado.

- Hacer: Se realizan los cambios para implantar la mejora propuesta. Generalmente conviene hacer una prueba piloto antes de realizar los cambios a gran escala.
- Verificar: Se monitorea la implementación y se evalúa el plan de ejecución, documentando las conclusiones (resultados y aprendizajes).
- Actuar: A partir de los resultados conseguidos en la fase anterior, se procede a recopilar lo aprendido y a ponerlo en marcha. También suelen aparecer recomendaciones y observaciones que suelen servir para volver al paso inicial de Planificar y así el círculo nunca dejará de fluir.

Figura 1. Ciclo de Deming



El presente artículo se focalizará en la aplicación de una mejora en una empresa de servicios petroleros, con el fin de lograr una optimización en tiempos de un proceso. Esto está estrechamente relacionado con el concepto japonés Kaizen (kai, que significa "cambio" y "zen", que significa "bueno" o "beneficioso"). Kaizen simboliza mejora continua en la vida personal, en el hogar, en lo social y en el trabajo, basado en acciones concretas, simples y poco costosas, que atraviesan a la organización en todos los niveles, desde los gerentes hasta los operarios. [3]

El contexto actual y la escasez de personal presencial, el home office y las prácticas asociadas llevaron a planificar de otro modo el flujo de la información y las formas de comunicación dentro de las compañías.

2. Descripción del sistema bajo estudio

2.1 Halliburton Argentina

Halliburton Argentina posee en Bahía Blanca, Buenos Aires, una planta de procesamiento de minerales situada en el área de acceso al puerto de la ciudad. En la Fig. 2 se observa el predio de la planta y los diferentes sectores dentro del área ejecutiva. La misma posee dos molinos que procesan un mineral, la Baritina, obteniendo dos productos finales: Barita a granel y en bolsones. La compañía trabaja

en las instalaciones de la empresa Sea White S.A. (SW), la cual es la principal proveedora de servicios para que Halliburton desarrolle su labor.

Dentro de la organización, se encuentra el área de Materiales, cuya función radica en la óptima gestión de inventario en almacén y su flujo desde que se procesa la materia prima hasta que el producto terminado llega a las manos del cliente. Para registrar estos movimientos de materiales, la empresa utiliza la tecnología SAP como ERP (Enterprise Resource Planning, por sus siglas en inglés). Se calcula que entre el 70% y el 80% del mercado de grandes empresas utilizan sus productos. [4]

Figura 2. Localización de sectores dentro de la Planta Sea White – Halliburton



2.2. Operación de la Planta

El proceso inicia cuando la materia prima (Piedra de Baritina) ingresa a premolienda, para aquellas piedras que requieran reducir su tamaño para utilizarse en los equipos posteriores. Una vez consumida esta etapa, el producto se dirige al sector de Molienda, donde se encuentra dos molinos, operados por personal de Sea White. El producto final, con las condiciones de humedad y densidad adecuados, se almacenan a granel en un Silo y en bolsones en depósito. A partir de la fabricación de estos productos finales, se generan las denominadas Ordenes de Producción (OP). Estas últimas son ingresadas a SAP por Halliburton por medio de diferentes operaciones llamadas Transaction Code (T-CODE).

Estos materiales producidos tienen una demanda real y son solicitados por clientes internos y externos. Los clientes internos son las demás bases que posee Halliburton a lo largo del país (Neuquén – Buenos Aires – Comodoro Rivadavia y Mendoza, entre sus principales) y los clientes externos son las operadoras que requieren el material directo en pozo o en sus almacenes intermedios. Cuando el material se envía directo

al cliente, se genera una Orden de Venta (SO - Sales Order, por sus siglas en inglés) En cambio, cuando el destino final es un cliente interno, se requiere una Orden de Transporte (TO – Transport Order, por sus siglas en inglés) y en la cual nos vamos a centrar en el presente trabajo.

2.3. Procesamiento de una Orden de Transporte

Una Orden de Transporte o Transport Order (TO) es una transacción utilizada en SAP para reflejar movimientos de materiales entre las locaciones que posee Halliburton a nivel país. La generación de esta nace cuando el cliente interno solicita una determinada cantidad de material para una locación en particular. El equipo de Planificación de la Demanda (DP - Demand Planning, por sus siglas en inglés) es el responsable de generarla y debe detallar el origen, el destino, el número que identifica al material, las cantidades requeridas, el costo del flete, entre otros. Al completar esta información, SAP crea un número de TO para este movimiento.

El proceso de generación de TO para Tolvas de Barita a Granel se compone de las siguientes etapas (Fig. 3):

1) El área de Materiales de Halliburton solicita a DP la creación de una TO. Se deben detallar la planta origen, la planta destino, el número de material y la cantidad requerida. Generalmente se solicita por un período de siete (7) días para evitar solicitar TOs de manera reiterada.

2) La barita se carga en camiones tolva a través de un silo. Por cada unidad, el área de Molienda de SW emite la documentación necesaria para procesar el viaje. El documento más importante es el Remito, donde se detalla el número de TO correspondiente al viaje.

3) Los remitos, una vez elaborados, se envían al área de Balanza.Esto implica el traslado de estos desde las instalaciones de la molienda. Finalmente, son cargados al sistema de SWpor personal del área de Balanza.

4) El área de Materiales de Halliburton descarga los remitos desde el sistema donde fueron cargados.

5) Terminada la semana, se procesa la TO, es decir, se ejecuta el despacho SAP. Se envía un e-mail con las personas implicadas y se adjuntan los remitos asociados a la TO semanal. Asimismo, se brinda un detalle en una tabla de Excel para tener trazabilidad.

Este proceso descripto presenta falencias identificadas tanto desde el equipo de Halliburton como el de Sea White. Ante esta situación, se determina en conjunto, idear alguna alternativa para mejorar el proceso.

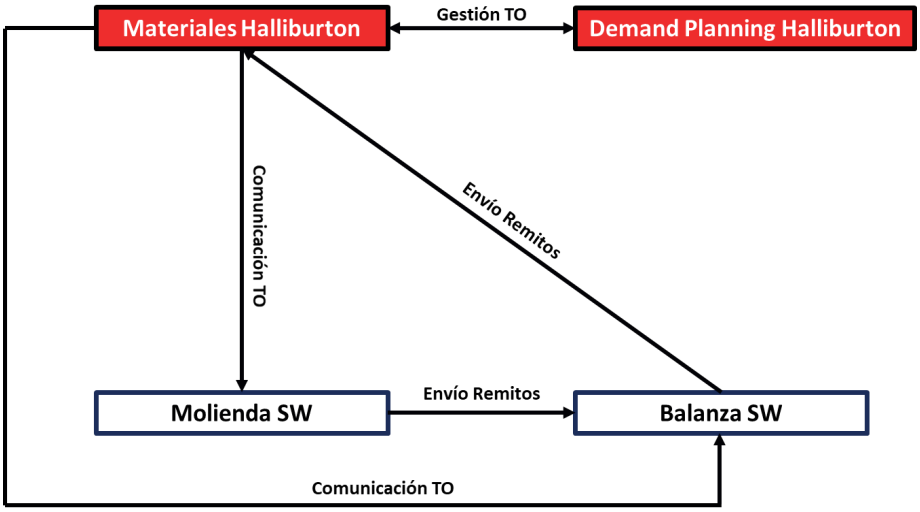


Figura 3. Flujo de documentación original

2.4. Detección en el proceso de potencial mejora

Respecto al proceso, se detecta que en el punto 3 un potencial cambio para mejorar el proceso: los remitos físicos se envían a Balanza por intermedio de alguno de los operarios de los molinos. Una vez hecho esto, personal de la Balanza los escanea y los sube al sistema para que personal de Materiales de Halliburton pueda tenerlos a disposición.

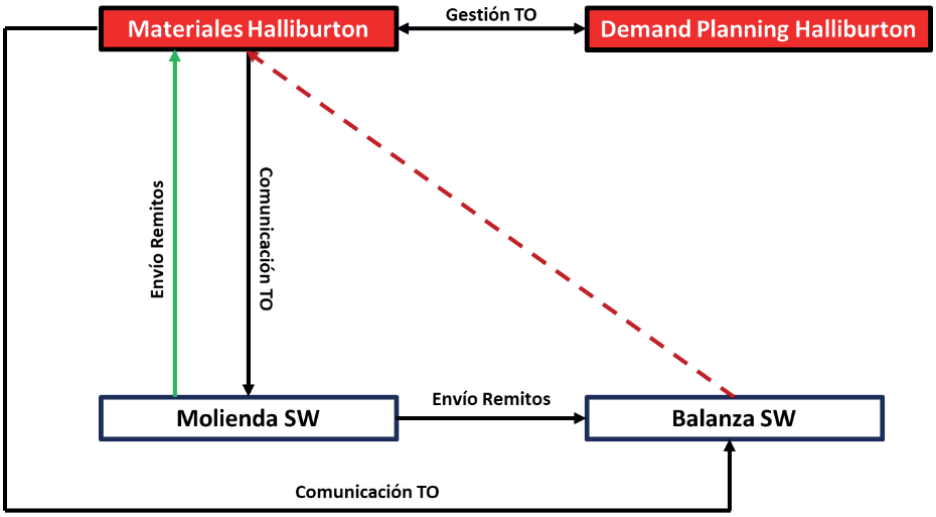
2.5. Cambios implementados

La situación actual generaba que los remitos físicos corran el riesgo de dañarse, perderse en el camino u otro motivo que pudiera evitar su llegada óptima a la Balanza. Asimismo, no se enviaban diariamente ya que los operarios no tenían siempre disponibilidad de hacerlo y el tiempo para enviarlos no era siempre el mismo. Muchas veces los llevaban a fin de la semana o a comienzos de la próxima semana, lo que complicaba el procesamiento de estos para personal de la Balanza y la disponibilidad para Halliburton.
Ante esto, a través de intercambios entre las partes afectadas, se detectan posibles cambios que pueden mejorar el flujo de esta documentación, a saber:

1) Principalmente se elimina el flujo de remitos enviándolos por medio de los operarios desde la Molienda hasta la Balanza. La línea punteada color rojo detalla esta anulación (Fig. 4).
2) Personal de Molienda toma el rol de escanear los remitos en la Sala de Control sin que les implique un retraso en sus actividades diarias.

3) Personal de Molienda acuerda con Materiales de Halliburton y Balanza de SW enviar un e-mail con los remitos escaneados, el mismo día que pasan la Orden de Producción. La línea verde detalla este nuevo recorrido (Fig. 4).
4) Halliburton Bahía Blanca acuerda con Halliburton Neuquén realizar un despacho intermedio en vez de realizar un despacho por el total para poder procesar viajes por SAP con mayor agilidad.

Figura 4. Flujo de documentación modificado



3. Resultados

Este pequeño cambio en el flujo de la documentación dentro de la planta se comenzó a implementar en septiembre del año 2020, y tuvo un impacto positivo en el procesamiento de la información, tanto para SW como para Halliburton.

Las principales mejoras se detallan a continuación:

a) Ahorro en distancia recorrida en envío de remitos a Balanza y Materiales.

Proceso anterior: Personal de Molienda debía recorrer una distancia promedio de 500 (metros) contemplando ida y vuelta al sector de Balanza.

Proceso actual: Distancia promedio de 0 (metros).

b) Materiales evita consultar por diferentes medios en reiteradas ocasiones a la Molienda y a la Balanza para que les brinde los remitos.

c) Se evita el manipuleo excesivo de los documentos.

d) Balanza puede cargar los remitos a su sistema de manera más rápida y sencilla.

e) Materiales Bahía Blanca baja el tiempo de procesamiento de la TO.

Proceso anterior: El tiempo de procesamiento promedio era de 10 días.
Proceso actual: El tiempo de procesamiento promedio es de 7 días.

f) Disminución en el tiempo de procesamiento impacta positivamente en el procesamiento de la TO en el destino final [Silos de Barita en Cipolletti, Río Negro].

Proceso anterior: Las TO que se procesaban fuera del mes en el que ocurrían.
Proceso actual: Las TO pueden ingresar dentro del mes que corresponde, dando una visión más real de los números contables.

g) Al procesar menor cantidad de viajes se evita caer en el re-trabajo o reprocesamiento de los documentos. Asimismo, aumenta el control de factores clave como el peso neto de material enviado o el número de TO detallado en el remito, permitiendo detectar errores con antelación y así corregir a tiempo diferencias que pueden producirse en el trayecto.

h) Materiales le empezó a solicitar a Demand Planning que genere la TO por un valor mayor a lo que se pedía con anterioridad. El coordinador de Materiales propuso pasar de 600 (Ton) a 1,500 (Ton). Los despachos de la TO siempre se pueden hacer por encima del valor por el que fue generada la TO pero hay límites para que SAP permita avanzar con el delivery. El objetivo de este cambio es poder realizar el despacho sin esperar que intervenga Demand Planning, al menos hasta que ajuste la TO por exceso o por defecto.

Tabla 1. Cuadro comparativo entre proceso anterior y actual

Concepto	Proceso Anterior	Proceso Actual
Distancia recorrida	500 metros	0 metros
Consulta Remitos	Gran intercambio de mensajes vía e-mail, llamados telefónicos, presenciales	Menor intercambio de mensajes vía e-mail, eventuales llamados telefónicos por alguna omisión
Manipulación Documentos	Varias áreas y personas implicadas (Molienda, Operarios, Balanza)	Solo personal de Molienda maneja la documentación original

Carga de Documentos SW y Halliburton	Lento Balanza debía esperar los remitos físicos desde Molienda	Ágil La carga se produce cuando la Molienda pasa la producción del día
Tiempo promedio procesamiento TO – Planta Barita	10 días	7 días
Tiempo promedio procesamiento TO – Silos Cipolletti	Procesamiento lento Más de un mes para el cierre de la TO	Las TO se pueden procesar dentro del mes, reflejando la realidad
Despachos	Un (1) solo despacho por el total de toneladas Doble trabajo por errores arrastrados Reprocesamiento de TO por SAP	Dos (2) despachos parciales por TO Mayor control de documentos Disminución de errores Correcciones anticipadas

4. Conclusiones

Al desarrollar esta experiencia de cambio dentro de la organización, se puede notar como pequeños cambios pueden generar impactos significativos dentro de un proceso y de una cultura organizacional, para hacerlo más dinámico y eficiente. La flexibilidad y apertura a nuevas formas de trabajo permite construir escenarios propensos a la mejora continua, en cualquier área de una compañía. Adicionalmente, en este estudio de caso particular, tanto cliente como proveedor trabajan in situ, siendo ambos beneficiados con la mejora implementada. Consecuentemente, las mejoras en los procesos correspondientes al proveedor mejoran los del cliente y viceversa. Este concepto tan arraigado a culturas orientales no distingue entre personas, organizaciones, rubros, tamaño de empresas. Es importante detectar puntos de mejora, establecer equipos de trabajo puntuales y desarrollar planes de acción. Aplicar el Ciclo de Deming (PDCA) en cualquier nivel organizacional crea una cultura de mejora continua que desemboca en la búsqueda de niveles elevados de performance en todo campo en el que se implemente.

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ICPR-Americas 2020

SEMINARIO DE ENSAYO ESTUDIANTILES

Prefacio

Seminario de Ensayos Estudiantiles ICPR-Americas 2020

Prefacio Este volumen incluye los artículos presentados en el "Seminario de Ensayos Estudiantiles" de la "*Xth International Conference of Production Research-Americas*" (ICPR-Américas 2020), realizado en forma virtual en Bahía Blanca, Argentina del 9 al 11 de diciembre de 2020. Este Seminario fue organizado por un comité organizador local de la ciudad de Bahía Blanca y fue auspiciado por la *International Foundation of Production Research* (IFPR). El Comité local estaba constituido por:

Antonelli María Mercedes (Dpto. de Ingeniería, Universidad Nacional del Sur, Argentina)
Barrera Alejandra (Dpto. de Ingeniería, Universidad Nacional del Sur, Argentina)
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El Seminario permitió que estudiantes de grado pudieran participar del ICPR-Americas 2020 de forma activa. Para ello debieron escribir un ensayo de entre 1000 y 1500 palabras sobre alguno de los pilares propuestos por el comité organizador. Los pilares fueron: Industria 4.0, Internet de las Cosas, Energías Renovables, Manejo Sustentable de Residuos, Supply Chain Sustentable y/o Economía Circular, Smart City y/o Construcción sustentable. Los ensayos fueron evaluados por los miembros del comité organizador, pudiendo ser rechazados, aceptados con revisiones o aceptados. Luego, los trabajos que pasaron el proceso de revisión se presentaron durante el ICPR-Americas 2020 por sus propios autores. A la presentación de los mismos atendieron distintos investigadores y participantes del ICPR-Americas 2020. Agradecemos enormemente la colaboración y el compromiso de todo el comité organizador, así como de los/as participantes. El Seminario brindó la oportunidad de participar en una conferencia internacional a estudiantes de grado de forma activa y concreta, permitiendo su involucramiento en actividades de elevado nivel académico.

Marzo 2021

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Economía Circular: El flujo de información en la Cadena de Suministro

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Resumen. La administración de la cadena de suministro tiene un papel clave en la reducción de desechos y contaminantes, que las empresas generan como impacto negativo en el medioambiente. La economía circular es un modelo que intenta desvincular el desarrollo económico global del consumo de recursos finitos y propone, junto con un modelo restaurativo y regenerativo, un flujo de información y un flujo de materiales que respaldan la reducción junto con la circularidad. La SC, vista desde una perspectiva integradora, debe subordinar sus diferentes niveles a las nuevas direcciones que entraña esta evolución, valiéndose sus administradores de los sistemas de información para tomar decisiones que orienten los resultados a estos nuevos sentidos. La información, como dimensión que atraviesa la SC en su totalidad, adopta en este cambio de paradigma, un flujo tanto lineal o clásico como circular, que será el pilar para concretar acciones que contribuyan a los puntos fundamentales de esta economía sustentable.

Palabras clave: Cadena de suministro, SC, economía circular, flujo de información.

1 Introducción

La economía circular es el modelo económico estratégico que pretende reemplazar al modelo lineal actual, basado en "tomar, hacer y desechar", o su paralelismo, "comprar, usar y desechar", por uno que tiene como objetivo final ser restaurativo y regenerativo. Este concepto introducido en 1989 por David W. Pearce y Robert K. Turner en su trabajo "Economics of Natural Resources and the Environment", no ganó demasiada popularidad en aquel tiempo, en comparación a los conceptos de "Eco-eficiencia" y "Las tres R" –reducir, reutilizar y reciclar-. Las compañías tomaron conciencia de la creciente preocupación por el medio ambiente, anexada a la consecuente difusión en estos dos términos, y no tardaron en adoptar la premisa de que menos era mejor. De esta manera, a finales del siglo XX, las empresas consiguieron ahorrar en costos y obtener mayores beneficios mediante una reducción de recursos, uso de energía, emisiones y desperdicios, disminuyendo los daños colaterales de sus actividades, al mismo tiempo que su imagen pública mejoró [1]. Sin

embargo, no pareció presentar un gran cambio en sus estructuras, y ¿acaso la reducción de desechos elimina la continua generación de los mismos?

De forma adicional a los objetivos ambientales en común que pudieran tener estas concepciones, la economía circular reconoce que reducir no es una solución a largo plazo, e innova tomando como eje central de la estrategia, una desvinculación de los recursos naturales finitos, con punto de partida en el diseño de los productos y los procesos.

La cadena de suministros, que abarca todas las actividades relacionadas con el flujo y transformación de bienes, desde la etapa de la materia prima hasta el usuario final, en este nuevo modelo mantiene su rol principal. Los materiales y la información, que fluyen en sentido ascendente y descendente [2] en la cadena de suministros adquieren en el sistema circular nuevas direcciones. Por ende, será sustancial en este escenario reforzar al máximo el control y la subordinación de la SC, a la obtención de los nuevos objetivos ambientales que sobrepasan el mero beneficio económico. Una mejor administración del flujo de información será sustancial para lograr la efectividad en las operaciones consecuentes a estas metas.

2 La economía circular y el flujo de información

2.1 Definición de Cadena de Suministro

Las definiciones en torno a la cadena de suministro, según la literatura y dependiendo del enfoque, han sido diversas a lo largo del tiempo. En general, el flujo de materiales ha logrado ser el centro de este concepto, o al menos, el elemento de rápida asociación del mismo. Sin embargo, se vuelve necesario distribuir la atención a las otras dimensiones de SC, que no sólo están constituidas por los distintos tipos de flujo (material, información y dinero), sino también por un horizonte de tiempo (estratégico, táctico y operacional), ambos relacionados de forma simultánea con los diferentes centros de decisión tales como transporte, inventario y locación [3]. El flujo de información será entonces, la base donde se apoyarán las decisiones y relaciones entre el resto de elementos y dimensiones de la SC.

2.2 Marco ReSOLVE

La fundación Ellen MaCArthur, cuya meta es promover la economía circular, propuso junto a la compañía McKinsey & Co, el marco ReSOLVE. Este marco hace de guía para las empresas que pretenden avanzar hacia este modelo circular, y se compone de seis acciones: Regenerate (regenerar), Share (compartir), Optimise (optimizar), Loop (bucle), Virtualise (visualizar) y Exchange (intercambiar) [4]. Al conocer que estas acciones implican conductas tales como incrementar rendimientos y eficiencias de los productos, eliminar residuos en la producción y en la SC, utilizar la automatización, refabricar productos y componentes, reciclar materiales, cambiar transporte clásico a multimodal, entre otras, la importancia del flujo de información toma mayor relevancia.

2.3 Beneficios para la empresa en la Economía Circular

Según algunas investigaciones realizadas por la fundación y la consultora McKinsey & Co entre 2013 y 2015, algunas oportunidades de beneficios incluirían una reducción del costo de fabricación de celulares, que podría disminuir en hasta un 50% por dispositivo, si la industria fabricase teléfonos más fáciles de separar, facilitando el ciclo inverso y ofreciendo algún incentivo a los clientes para devolver los teléfonos [5].

Por otro lado, las lavadoras de alta gama, resultarían más accesibles para la mayoría si se alquilasen en vez de venderse, y según las investigaciones, los clientes ahorrarían aproximadamente un tercio por ciclo de lavado y el fabricante ganaría en torno a un tercio más en beneficios [5].

Además, en Reino Unido, cada tonelada de ropa recogida y reutilizada podría generar unos ingresos de 1975 USD, o un beneficio neto de 1295 USD si se reutilizan en la industria textil [5].

2.4 Análisis del flujo de información en la Economía Circular

Un conocimiento integrado de las diferentes dimensiones de la SC, que responda a cuestiones tendientes a encontrar errores y posibles mejoras, a lo largo de cada proceso de operaciones (planeación, fuente o proveedores, manufactura, entrega y devolución) [6], será clave para conquistar las acciones propuestas.

La planeación, constituye una función principal para conseguir los objetivos principales de esta economía; “reducir” y “devolver”. Debido a que este proceso, tanto en el modelo lineal como en el circular, se nutre de datos históricos, se vuelve necesario procesar información de tiempos estándares, rutas, distancias, capacidades y otros, para lograr una eficiente operación. Recursos como modelos y redes de distribución, que utilizan algoritmos o métodos de programación lineal, pueden mejorar la eficiencia de transporte y entrega, reduciendo así, los viajes y las consecuentes emisiones de gases contaminantes al medioambiente.

La información es y será la piedra angular para la toma de decisiones que determinarán desde niveles de inventario hasta posibles perfeccionamientos en la productividad de máquinas y operarios, que es y seguirá siendo un aspecto clave en la reducción de desechos. En la manufacturación, las herramientas adecuadas incluyen desde sistemas de visualización de información de plantillas de trabajo de operario, hasta cálculos de tiempos estándares destinados a incrementar productividad mediante estudios de movimientos, tal como en el modelo lineal, pero planeando la eficiencia desde el diseño. En el caso de los dispositivos celulares, deberá tenerse en cuenta una base de diseño que permita la reutilización. De esta forma, se supone un flujo de información que se dirige desde los resultados de procesos productivos y funciones posteriores hacía los procesos iniciales de la SC, vinculado a la producción y al diseño. Esta dirección, central en el modelo actual, será igual de importante en la economía circular. En adición, será necesario despegarse del punto de partida de materiales vírgenes o componentes diseñados para un modelo particular.

La información que fluye por la S llega a la devolución, que en el modelo clásico significaba el retorno de productos fallados, y en el nuevo sistema considera el reingreso de productos o componentes en desuso que podrían ser reutilizados, como en los ejemplos de dispositivos celulares o ropa reciclada. De esta forma, se manifiesta la necesidad de un mayor seguimiento de los bienes comercializados, luego de la función de entrega. En esta cuestión herramientas como sistemas de información pueden apoyar las decisiones de localización relacionadas a los centros de devolución. Así pues, el flujo de información se extiende a lo que podrían ser puntos de recogida, y se puede plantear que esta estructura circular introduce, a su vez, un requerimiento de "devolución de la información", que incluye la importancia del conocimiento en instancias posteriores a lo que se consideraba como límite final de la SC.

Por otro lado, el flujo de información a través de la cadena de suministro, debe alcanzar también a los servicios y relaciones vinculados a los clientes. Como punto de partida, la adopción de una estrategia sustentable crea valor y genera un cambio en la percepción de los clientes. No obstante, este nuevo modelo requiere de una relación con el cliente, de mayor durabilidad y confianza que el vínculo requerido por el modelo lineal. Debido a la evolución de un sistema basado en "built in obsolescence", a un modo de fabricación "built in durability", la dependencia de clientes a empresas y viceversa, implica otra reestructuración. Por lo tanto, la información debe fluir también, desde los consumidores hacia las empresas, para ser considerada en las decisiones que las organizaciones tomen.

3 Conclusión

La evolución a la innovadora economía circular implicará no solo circularidad de flujo de materiales, sino un flujo circular de información. El procesamiento de datos no tendrá como principal finalidad mejorar la eficiencia de las operaciones de manufactura, sino que deberá ir más a allá de lo que el modelo lineal consideraba como límite final de la cadena de suministro. Esta circularidad entraña un cambio de paradigma en la administración de este flujo, y de la dimensión de flujos en general. Por lo tanto, deberán integrarse a través de sistemas de información, todas las funciones y elementos de la SC, de la misma forma que en el modelo clásico y añadiendo nuevas direcciones, que impliquen tanto la reducción como la devolución. Adaptando el uso de la información a estos nuevos sentidos, podrá cumplirse de forma simultánea un compromiso con el objetivo sustentable y un triple objetivo económico, social y ambiental.

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Actitud renovable

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Resumen. El calentamiento global es uno de los mayores problemas ambientales presentes en la actualidad. Aún con las medidas que se han tomado hasta el momento, queda un largo camino por recorrer para lograr revertir los daños causados por dicha cuestión. Una de las medidas más acertadas es la sustitución de los hidrocarburos como fuente de energía por el uso de fuentes 'naturales' o 'renovables'. Es vital el compromiso de todos y cada uno de nosotros para lograr un mundo más limpio.

Palabras claves: Energías limpias, renovables, acuerdo de París.

1 Introducción

Desde finales del siglo XVIII y hasta mediados del siglo XIX el mundo sufrió una serie de cambios que alternaron completamente el estilo de vida como se conocía hasta el momento. De la mano de la revolución industrial se vivió una de las transformaciones socioeconómicas más importantes de la historia de la humanidad, dejando atrás una vida rural basada casi por completo en la agricultura y la ganadería, dando lugar a una vida urbana, con la economía industrializada y mecanizada.

La invención de las máquinas de vapor para la industria textil, pasando por la iluminación doméstica, y así como el uso de miles de kilómetros de ferrocarriles, fomentaron el uso de hidrocarburos como fuente de energía a nivel mundial. Con el paso de los años, este consumo vio un crecimiento exponencial de la mano de los derivados del petróleo y la aparición del gas natural en la matriz energética [1].

Este consumo masivo de hidrocarburos derivó en lo que hoy en día conocemos como calentamiento global, producido por los gases de efecto invernadero (de aquí en más, GEI). Los principales GEI son el vapor de agua (H2O), el dióxido de carbono (CO2) y el metano (CH4) [2]; dichos gases pueden obtenerse con la combustión de los hidrocarburos presentes en el petróleo, el gas natural, el carbón, entre otras. El calentamiento global aumenta la temperatura superficial del planeta Tierra a velocidades alarmantes, efecto que se ve evidenciado en el súbito derretimiento y desprendimiento de glaciares y la consecuente elevación del nivel del mar [3].

A pesar de que algunas consecuencias del calentamiento global ya son irreversibles, no es tarde para alivianar las que aún están por venir. Para esto, naciones de todo el mundo firmaron el Acuerdo de París, dentro del marco de la Convención Marco de las Naciones Unidas sobre el Cambio Climático. Dicho acuerdo se basa, principal-

mente, en ‘‘reforzar la respuesta mundial a la amenaza del cambio climático manteniendo el aumento de la temperatura mundial en este siglo muy por debajo de los 2 grados centígrados por encima de los niveles preindustriales, y proseguir los esfuerzos para limitar aún más el aumento de la temperatura a 1,5 grados centígrados’’ [4]. Al ser un objetivo ambicioso, los organismos gubernamentales han de buscar las mejores alternativas para cumplir con lo estipulado en el Acuerdo.

El objetivo de este ensayo es presentar el panorama actual de las energías renovables, su importancia y su proyección a futuro.

2 Desarrollo

Considerando que tres de los principales GEI son producto de la combustión de hidrocarburos, no es difícil suponer que encontrar una alternativa eficiente y rentable a éstos favorecería las condiciones ambientales en donde se apliquen. Por eso, la mayoría de los países participantes de la Convención Marco de las Naciones Unidas sobre el Cambio Climático apuestan fervientemente al uso de Energías Renovables.

Se denomina Energía Renovable a ‘’aquellas fuentes energéticas basadas en la utilización del sol, el viento, el agua o la biomasa vegetal o animal -entre otras-. Se caracterizan por no utilizar combustibles fósiles…’’ [5]. Entonces, una energía renovable es aquella energía que se obtiene de fuentes naturales, que son capaces de regenerarse por sus propios medios o que contienen una inmensa cantidad de energía que, a fines prácticos, se considera inagotable. Las principales energías renovables son:

- la energía **eólica**, aprovechando la energía cinética del viento;
- la **geotérmica**, aprovechando el calor transmitido desde el interior de la Tierra;
- la **hidroeléctrica**, aprovechando la energía cinética y potencial de los cuerpos de agua;
- la **mareomotriz**, similar a la hidroeléctrica, aprovechando las mareas de los mares;
- la **solar**, aprovechando la radiación electromagnética procedente del Sol;

- la **biomasa** y los **biocombustibles**, materia orgánica utilizable como fuente de energía;
- la **energía nuclear**, energía que se libera espontánea o artificialmente en las reacciones nucleares;

En los últimos años, la obtención de energía mediante estas fuentes tuvo una evolución muy favorable. Alentadas por las altas emisiones de GEI, la producción de energías renovables crece un 7.1% anual, representando más de la mitad del crecimiento en energía global. Como se presenta en la siguiente figura, estas fuentes constituyen hoy en día un 4% de la matriz de energías primarias, y se espera que para 2040 representen un 15% de la misma [6].

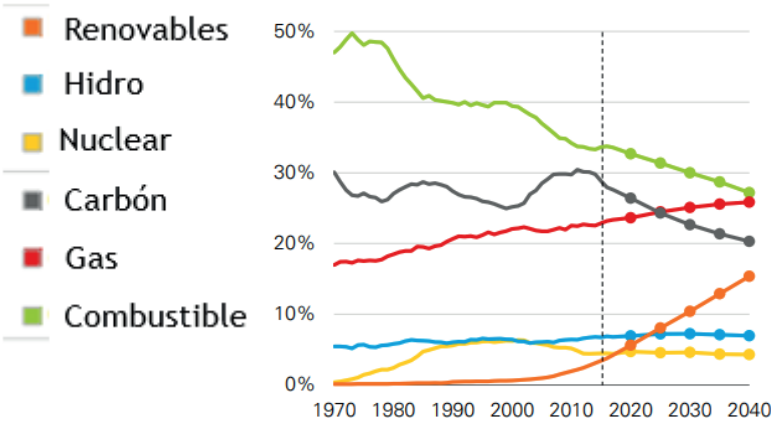

Fig. 1. Porcentaje de consumo de energía por distintas fuentes

El auge de las fuentes limpias y los rápidos avances tecnológicos trajeron con sigo una reducción de costos en los equipos necesarios para el desarrollo de estas, lo que favorece aún más el panorama ambiental para los años venideros. Las principales tecnologías renovables –como la eólica y la solar fotovoltaica- están reduciendo drásticamente sus costes, de forma que ya son competitivas con las convencionales, no solo para organismos gubernamentales o empresas multinacionales, sino también para el uso doméstico.

Por supuesto, la elección de la fuente de energía alternativa depende fuertemente de las condiciones geológicas y climatológicas del lugar. Por ejemplo, Uruguay invierte cerca de un 3% de su Producto Interno Bruto en una reforma estructural para alcanzar una conversión completa a energías limpias; dicha inversión logró que en 2019 el país funcionara en un 98% con energías renovables, siendo la hidroeléctrica y la eólica las preferidas por los uruguayos.

Argentina, a pesar de que todavía está lejos de alcanzar una independencia energética con respecto a los hidrocarburos, cuenta en su matriz con diversas formas de energía renovable. Según el balance energético nacional, desarrollado por la Secretaría de Energía de la Nación, la producción de Energía Hidráulica se encuentra en mayor proporción con aproximadamente 3 millones de TEP (Toneladas equivalentes de petróleo), seguida por la producción de Energía Eólica, con aproximadamente 559 miles de TEP. La Energía Solar no se encuentra muy presente en el país, produciendo sólo 69 miles de TEP. Es importante mencionar la contribución de la Energía a partir de biomasa (bagazo, leña, etc.) y biocombustibles (aceites y alcoholes vegetales) a la matriz energética, ya que, en conjunto, aportan cerca de 4,6 millones de TEP. Vale la pena mencionar que Argentina cuenta con potencial para producir Energía Nuclear, otra forma de energía renovable, pero los peligros que esto puede traer hacen que sea imposible la utilización de dicha tecnología [7].

A pesar de que el Acuerdo de París fue firmado por los gobernantes de cada país, la idea de cumplir los objetivos sólo con inversiones y trabajos públicos es una utopía. Por lo tanto, empresas de carácter privado han realizado su aporte a la causa, así como también lo hace el común de la gente con el uso doméstico de energías limpias, a pesar de la gran inversión económica que esto implica [8].

Los avances tecnológicos y el compromiso, tanto del sector público como el sector privado, presentan un panorama alentador en lo que respecta a la reestructuración energética mundial; aun así, esto tampoco significa que se cumplirá el objetivo, ya que no todo el mundo colabora de la misma manera. Países como Uruguay, Islandia y Noruega lideran la carrera en homogeneizar la producción de energía con fuentes renovables; el problema es que estos países no son los que mayor huella de carbono tienen. Estados Unidos, que secunda el ranking de países con mayores emisiones de CO2 en el mundo [9], decidió abandonar el Acuerdo de París, alegando que las condiciones no eran justas para dicho país, aunque se comprometían a trabajar ‘’para garantizar que Estados Unidos se mantenga como el líder mundial en temas ambientales, pero bajo un marco que sea justo…’’. Así, queda evidenciado que no todo el mundo profundiza la situación de la misma manera, aunque, en rasgos generales, afecte a todos por igual.

3 Conclusión

Considerando el paradigma energético nacional y mundial, se ve que los objetivos del Acuerdo de París son, como se dijo anteriormente, muy ambiciosos. A pesar de todo, se espera que en los próximos años la matriz energética global se encuentre más repartida entre las distintas formas de energías alternativas con respecto a las fuentes convencionales, a causa de las reestructuraciones y políticas de cada país, así como con el compromiso ciudadano, que, sin realizar una inversión de gran envergadura, puede aportar su grano de arena, reduciendo el uso del automóvil y los ascensores fomentando la bicicleta, la caminata y el uso de escaleras, respectivamente; también con la regulación de distintas actividades cotidianas que probablemente sean resultado de malos hábitos y costumbres, por ejemplo, ducharse por más de 5 minutos, prender las hornallas o el horno para aclimatar la habitación, el uso de aires acondicionados a temperaturas muy bajas, entre otras cosas.

La Tierra es una sola, y sin el compromiso de todas las partes, en poco tiempo el daño será irreversible. Está en cada uno hacerse cargo y tomar cartas en el asunto, o cruzarse de brazos y ver como el planeta se deteriora completamente.

‘’Cambiar a energías renovables, no es sólo la mejor opción. Es nuestra única opción’’ [10].

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Construcción sustentable y smart city

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Resumen. La industria de la construcción es una de las más contaminantes en la actualidad, presentando valores de emisión de gases y consumo de energía alarmantes. Si bien hasta el momento se han realizado numerosos avances y mejoras en la producción, todavía hay un gran camino por delante hacia una construcción más sustentable, con menor huella medio ambiental y la posibilidad de desarrollar el concepto de "Smart city" alrededor del mundo.

Palabras claves: Smart city, construcción, huella medio ambiental.

1 Introducción

La industria de la construcción tradicional tiene un importante impacto ambiental debido a la emisión de contaminantes atmosféricos, como los gases de efecto invernadero, y el gran consumo de energía. Además, los residuos provocados durante el proceso terminan contaminando tanto los recursos hídricos como el mismo aire que respiramos.

Mediante alternativas en los materiales de construcción, políticas e incentivos gubernamentales y cooperación entre los distintos sectores y la comunidad es posible disminuir la huella medio ambiental de la actividad y generar una mejora en la calidad de vida de las personas.

2 Desarrollo

2.1 Origen

Los principales impactos ambientales de la construcción tradicional son la emisión de contaminantes atmosféricos y el gran consumo de energía. Aproximadamente el 40% del consumo total de energía es causado por esta actividad a nivel global.

En el siguiente gráfico se muestra el porcentaje de emisiones de CO2 derivadas del consumo de combustible según el sector productivo. Se observa un alto porcentaje (38,6%) por parte de la industria manufacturera y construcción.

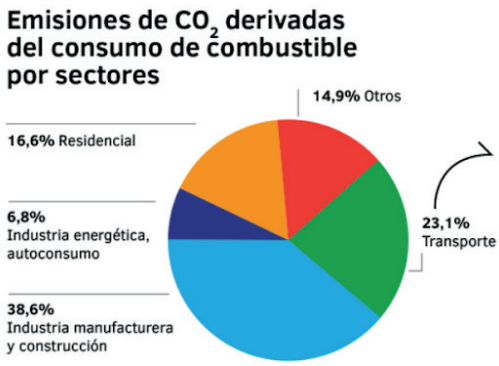

Fig.1. Emisiones de CO2 derivadas del consumo de combustible por sectores [6].

Además de los GHG se encuentran los contaminantes CAPs (Criteria Air Pollutants), grupo conformado por partículas en suspensión, óxidos de azufre y nitrógeno (SOx y NOx), monóxido de carbono y compuestos orgánicos volátiles; principales contribuyentes al smog y lluvia ácida. Los equipos de construcción generan una enorme cantidad de PM2.5 (partículas en suspensión de menos de 2.5 micras) y NOx, contaminantes influyentes en el asma, cáncer de pulmón, enfermedades cardiacas, cambio climático y el deterioro de la capa de ozono [2].

Por otra parte se encuentra la contaminación de recursos hídricos y los problemas de salud que genera. Se estima que millones de personas mueren cada año como consecuencia de enfermedades infecciosas transmitidas por el agua. El cambio climático agrava la situación .Se prevén sequias, olas de calor, inundaciones y tormentas más fuertes.

Centrándose en la construcción, se ve que durante el siglo pasado el hormigón/cemento fue el material más comercializado debido a su versatilidad, rendimiento, disponibilidad y bajo costo de materias primas; sin prestar atención a su impacto en el medio ambiente. Sin embargo, se espera que la demanda se incremente en regiones en desarrollo como India, Medio Oriente, Sudamérica y África; donde la urbanización se hará cada vez más presente [3].

2.2 Industria de la construcción

El trabajo de construcción en espacios abiertos y al aire libre genera de manera directa una gran cantidad de emisiones CAPs y polvo de la erosión de suelo, trituración de rocas y demolición de edificios (emisiones fugitivas).

Por otra parte, la implementación de un sistema sostenible se dificulta debido a la descentralización de la actividad, lo que obstaculiza la cuantificación precisa de sus impactos ambientales. Además de que la mayoría de las firmas de

construcción son pequeñas, como ningún proceso se repite en iguales condiciones que otro anterior no es posible comparar y juzgar una mejora en la gestión ambiental.

En esta situación se vuelve imprescindible desarrollar un método confiable y seguro para evaluar las emisiones en los procesos de construcción. En la actualidad se presentan dos metodologías: LCA (Evaluación del Ciclo de Vida) e EI-O LCA (Evaluación económica del Ciclo de Vida). El LCA evalúa efectos ambientales de edificios comerciales y residencias, desde la extracción de la materia prima hasta el mantenimiento y el final de la vida útil del lugar. Sin embargo, en su mayoría de aplicaciones se pasa por alto o se aborda incorrectamente el impacto ambiental de los procesos involucrados. El segundo método, EI-O LCA utiliza información de sectores separados y evalúa la interacción económica en dichos datos.

Otra parte importante es el trabajo con las empresas y la posibilidad de adoptar un modelo más ecológico. Para esto existen dos tipos de incentivos: programas de subvenciones y financiación directa para reemplazar equipos viejos por otros más nuevos y limpios, y en segundo lugar incentivos fiscales para incentivar el uso de tecnologías y disminuir las emisiones [2].

Actualmente, la construcción sustentable y los materiales de construcción con una huella medio ambiental reducida atraen el interés en la industria de la vivienda y construcción a nivel global. Gracias a esto se generaron cambios y avances beneficiosos para el ambiente tales como:

- Desarrollo de hormigón de geopolímeros de espuma con un mayor rendimiento y disminución en el consumo de energía y emisiones.
- Mejora de la eficiencia energética en plantas de manufactura.
- Uso de biocombustibles.
- Reciclado de residuos de construcción y demolición.

2.3 Nano sensores y avances tecnológicos

El rápido crecimiento del "Internet de las cosas" (Internet of things) abre nuevas posibilidades para la recopilación de datos urbanos de manera sencilla y segura. El IoT es un sistema que permite que los objetos sean controlados y detectados de manera remota a través de redes de infraestructura existentes. A partir de él surgió la idea de desarrollar el IoS (Internet de los sensores) capaz de monitorear en tiempo real los ambientes urbanos, a través de los parámetros necesarios y significativos. Algunas de las posibles aplicaciones del sistema serían: relojes inteligentes con datos locales de contaminación, redes de agua con auto diagnóstico de fugas o contaminación ambiental y sistemas de aire acondicionado que optimicen la calidad del aire [1]. Dentro de las ciudades las comunidades están comenzando a implementar cambios prácticos como reducción de la velocidad en las principales carreteras, reducción del tráfico pesado, multas por contaminación sonora y apoyo a los sistemas de transporte público y la movilidad

alternativa o verde. A su vez se ha comenzado a indagar sobre el concepto de ciudad sensitiva (Sense-city), que permitiría que la ciudad se auto diagnostique de manera constante con el fin de preservar el medio ambiente, ahorrar recursos y proteger a sus habitantes. Este proyecto se basa en la implementación masiva de micro y nano sensores en escenarios urbanos reales profundizando nuestro conocimiento acerca de su funcionamiento y dinamismo. Algunos de los puntos principales son:

- Desempeño energético de edificios y vecindarios.
- Infraestructura para la compilación de datos urbanos.
- Identificación por radio frecuencia (RFID) usado en monitoreo de la ciudad.
- Mapeo de contaminación.
- Carreteras foto-voltaicas.

2.4 Aplicaciones en América Latina

Unos de los ejemplos concretos de construcción sustentable y ahorro de recursos en América Latina es el museo denominado "Museo del mañana", ubicado en Rio de Janeiro, Brasil. Este edificio se define como autosuficiente y sostenible, rodeado por áreas verdes y estanques de agua. El techo, por otra parte, está compuesto por placas fotovoltaicas que cambian de posición durante el día en busca del mejor aprovechamiento del recurso.



Fig.2. Museo del mañana, Rio de Janeiro, Brasil [5].

Otro ejemplo para destacar es el edificio del Instituto del Fondo Nacional de la Vivienda para los Trabajadores (Infonavit), ubicado en Ciudad de México, donde se construyo la azotea verde más grande en la región. Este lugar, además de usarse como esparcimiento laboral, presenta una gran variedad de especies vegetales y un espacio donde se producen alimentos orgánicos [4].



Fig.3. Terraza edificio central Infonavit, Ciudad de México, México [4].

3 Conclusión

A partir de los datos e información indagados en el ensayo se ve una gran mejoría en la industria de la construcción y vivienda, habiendo empezado a implementar el uso de biocombustibles, generar materiales alternativos, facilitar a los propietarios el acceso a maquinaria nueva y menos contaminante, entre otras. Si bien hay un gran camino por recorrer para generar una conciencia responsable acerca de lo que la contaminación puede provocar en el medio ambiente y la salud de las propias personas, los avances son importantes y dan pie a nuevos cambios a futuro.

Las ideas y trabajos deben enfocarse no solo en mejorar la situación actual, sino permitir a generaciones futuras vivir en un mundo equilibrado y con buena calidad de vida.

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